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THE EFFECTS OF FLUIDS AND CYCLIC LOADING ON THE ELASTIC MODULI OF ROCKS

Phillip N. La Mori

Battelle Columbus Laboratories

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Cyclic Loading						

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ANNUAL REPORT

on

THE EFFECTS OF FLUIDS AND CYCLIC LOADING ON THE ELASTIC MODULI OF ROCKS

by

Phillip N. La Mori, Principal Investigator
Phone 614-299-3151 X3415

August, 1972

to

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ABSTRACT

Simultaneous volume and acoustic velocity measurements have been made to determine the elastic moduli of Salem limestone, Berea sandstone, and Westerly granite. The purpose was to examine differences and similarities between the two measurements. The effects of cyclic loading and water filling were also examined. Significant differences in bulk modulus are observed on pressure release and during crush up. While the volume value of bulk modulus decreases sharply at crush up only a slight knee or depression occurs in the velocity values. We have found the immediate pressure release values of volume bulk modulus to be greater than the corresponding acoustically determined values while the opposite is true on compression. This suggests that the acoustic pulse--which is a slight alternating pressure rise and decrease superimposed on the applied stress--averages the compression and release modulus. These results can be explained by Scholz's[21] statistical model of applied stress to local stress. The results can be shown to give a linear velocity versus density relationship for the limestone and sandstone. Several possible applications of these results to the sponsor's Hard Rock Excavation program are given.

THE EFFECTS OF FLUIDS AND CYCLIC LOADING ON THE ELASTIC MODULI OF ROCKS

by

Phillip N. La Mori

INTRODUCTION

The purpose of this research program was to utilize simultaneous acoustic and volume measurements in order to understand the differences and similarities between the dynamic and static elastic moduli of rocks. A second goal was to measure the effects of cyclic loading on these moduli. The effect of water filling was also investigated.

This program was initiated with the intent of studying rock types with widely different porosities and elastic properties that could be expected to be found in medium-to-hard rock excavation associated with the U. S. Bureau of Mines, ARPA sponsored, "Hard Rock Excavation Program". It was anticipated that this research program would provide a much clearer understanding of the differences in values of the elastic moduli of rock as measured by two different but widely used techniques. (Acoustic velocity techniques are widely used in field evaluations of rock properties and are also increasingly being used in the laboratory. Static or volume techniques are quite common in laboratory determinations of elastic properties.)

The elastic moduli of rock are the fundamental parameters needed to calculate excavation costs, excavation rates, and by means of sophisticated computer codes the effects of energy input on rock fragmentation. This information is vital to the sponsor's interest to obtain increased

excavation rates in hard rock by either (1) improvement of conventional methods or (2) development of new techniques. In order to make these calculations it is not only necessary to know the values of the elastic moduli but also how they were obtained and how these values represent the response of the rock to the method of excavation.

Conventional excavation techniques often do not remove the rock on the initial loading, i.e., the rocks are often cyclically loaded. Because rocks contain pores and microcracks this cyclic loading can cause significant changes in elastic properties. Knowledge of how the elastic properties of rocks change with cyclic loading would be essential to the sponsor if the changes are significant enough to any of the above calculations. If the changes are large enough and in the right direction they could suggest ways to improve excavation techniques.

Water is often present in significant quantities in rock. The effect of water on the elastic moduli--as measured by the two techniques--is important in increasing our understanding of rocks encountered in real excavation situations. These results are therefore quite pertinent to any application the sponsor might have.

Because this program was exploratory, three rocks with idealized chemistry and fabric were selected. Salem limestone, composed of approximately 100 percent calcite shell fragments has a porosity of approximately 12.5 percent but with a fairly high compressive strength of 10,000 psi, was chosen as a representative medium material. Berea sandstone was chosen as a harder material because of its quartz content and as a material with a high porosity of 19.1 percent. Westerly granite was chosen as a representative of very hard, dense, and low-porosity rock. This report describes results of tests on these materials.

BACKGROUND

Previous Work

It has been known since the first measurements on the compressibility of rocks[(1)*] that the effects of cracks and voids have a predominant effect at low confining pressures. Birch[(2)] suggested that at low pressure cracks and voids were strongly influencing the velocity of sound in rocks. Ide[(3)] was the first to point out discrepancies between the values of the elastic moduli of rocks as measured by static and by dynamic methods.

More recently, Simmons and Brace[(4)] compared the bulk modulus of the same rock determined by static and dynamic methods at pressures up to 8 kb. They found the dynamic bulk modulus to be significantly larger at low pressures; however, at higher pressures the difference decreased. They ascribed this difference to cracks that affect static moduli more than they affect the propagation of acoustic waves. Results from experiments to 40 kb (in which it was shown that the voids and the cracks were essentially removed) have indicated that the difference in bulk modulus determined by the two methods is in the relationship predicted by theory or within experimental error.[(5)]

Simmons and Brace compared results from separate static and dynamic experiments on different samples of the same rock. This technique is useful but has several disadvantages. One major disadvantage is that rocks of the highest homogeneity are still prone to local inhomogeneities; thus, it is difficult to make comparisons with absolute certainty. Also, certain effects tending to show up more in one experimental technique than the other, make difficult the direct comparison of interesting, experimental phenomena. The present program measures one acoustic velocity and the static volume

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* References are given on page 69.

change simultaneously on the same sample. Thus, local inhomogeneities become more easily recognizable and the experimental phenomena observed by each measurement can be compared simultaneously. An additional advantage of this technique is that the density value, required in the equation $C = f(\rho V^2)$, is also determined simultaneously (C = modulus, ρ = density, V = acoustic velocity).

La Mori[6] and Stephens[7] have shown that high hydrostatic confining pressure markedly affects the volume of certain rocks when they are returned to one atmosphere pressure. For example, rocks with a porosity greater than a few percent generally show a crush-up or decrease in volume after an excursion to high pressure. Rocks with a low initial porosity generally increase their volume after high pressurization. Figure 1 shows that cyclic pressurization on a dense granitic-type rock markedly affects the low pressure volume and bulk modulus ($= V \frac{dP}{dV}$) after each cycle to high pressure. These experiments suggest that a detailed examination at cyclic pressures would be quite valuable. From a practical point of view, rocks excavated by mechanical or explosive means generally are stressed several times to some pressure level above ambient before they are removed from the rock mass. Thus, an understanding of how cyclic loading changes the elastic properties of rocks may be useful in evaluating the effects of excavation techniques or devising a superior excavation technique.

Determination of Required Parameters

Determination of the elastic modulus by acoustic and volume techniques involves the fundamental assumption of elasticity theory: stress is proportional to strain.

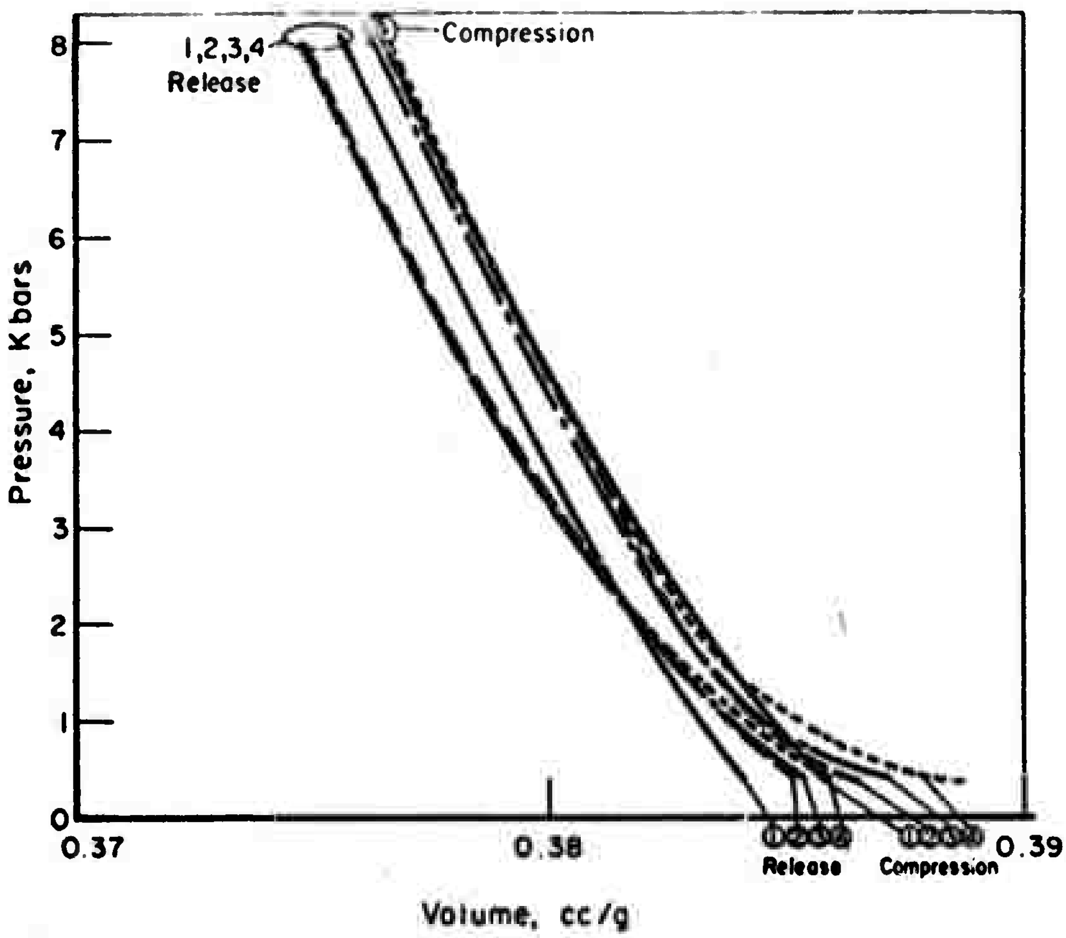


FIGURE 1. LOW-PRESSURE CYCLING DATA FOR DRY LOW-POROSITY GRANITIC ROCK[6]

$$\sigma_{ij} = C_{ijk\ell}\epsilon_{k\ell} \quad ,$$

where σ_{ij} = stress tensor, $C_{ijk\ell}$ = elastic constants of proportionality, $\epsilon_{k\ell}$ = strain tensor. As this assumption is used to form a generalized Hooke's law and derivation of the elastic moduli in many texts, it is not repeated here. It can be shown for the isotropic case that

$$\sigma_{xx} = (\lambda+2\mu)\,\epsilon_{xx} + \lambda\epsilon_{yy} + \lambda\epsilon_{zz}$$

$$\sigma_{yy} = \lambda\epsilon_{xx} + (\lambda+2\mu)\,\epsilon_{yy} + \lambda\epsilon_{zz}$$

$$\sigma_{zz} = \lambda\epsilon_{xx} + \lambda\epsilon_{yy} + (\lambda+2\mu)\epsilon_{zz}$$

$$\sigma_{yz} = 2\mu\epsilon_{yz}$$

$$\sigma_{zx} = 2\mu\epsilon_{zx}$$

$$\sigma_{xy} = 2\mu\epsilon_{xy} \quad ,$$

where λ and μ are constants chosen so $(\lambda+2\mu)$ relates stress and strain in the same direction and λ relates them in perpendicular directions.

The following moduli are usually defined:

Young's Modulus $\quad E_x \equiv \left(\dfrac{\Delta\sigma_{xx}}{\Delta\epsilon_{xx}}\right)$ all σ_{ij} constant except σ_{xx}

Modulus of Rigidity or shear modulus $\quad G_{yz} \equiv \dfrac{1}{2}\left(\dfrac{\Delta\sigma_{yz}}{\Delta\epsilon_{yz}}\right)$ all σ_{ij} constant except $\sigma_{yz} (= \sigma_{zy})$

Modulus of Incompressibility or bulk modulus $\quad B \equiv \left(\dfrac{\Delta\sigma_m}{\Delta e}\right)$, all σ_{ij} constant for $i \neq j$

$$e = \epsilon_{xx} + \epsilon_{yy} + \epsilon_{zz}$$

Poisson's Ratio is defined $\quad \nu_x \equiv -\left(\dfrac{\Delta\epsilon_{yy}}{\Delta\epsilon_{xx}}\right)$ all σ_{ij} constant except σ_{xx} .

For the isotropic case and the appropriate conditions

$$E = \frac{\mu\ (3\lambda+2\mu)}{\lambda+\mu},\ G = \mu,\ B = \lambda+2/3\mu,\ \text{and}\ \nu = \frac{\lambda}{2\ (\lambda+\mu)}\ .$$

The conventional means of determining the elastic moduli are direct static measurements. The experimental program determines the static values by axial and radial strain gages mounted on the sides of a cylindrical sample. Thus the bulk modulus is

$$B = -V_o\left(\frac{dP}{dV}\right) \text{ with } \sigma_{xx} = \sigma_{yy} = \sigma_{zz} = -P = \text{hydrostatic pressure.}$$

$$B = -\frac{P}{e} = \lambda+2/3\mu\ .$$

V_o = initial volume dV = volumetric change.

In the next stage of the program, E and ν will be determined at various confining pressures to 10 kb by varying σ_{xx} slightly from σ_{yy} and σ_{zz} using a triaxial cell

$$E = \left(\frac{\sigma_{xx}}{\epsilon_{xx}}\right)_{\sigma_{yy},\ \sigma_{zz}\ \text{constant}}\ ,$$

and

$$\nu = \left(\frac{\epsilon_{zz}}{\epsilon_{xx}}\right)_{\sigma_{yy},\ \sigma_{zz}\ \text{constant}}\ .$$

Then values can be computed for the other static elastic moduli, e.g., $G = \frac{E}{2\ (1+\nu)}$.

For the dynamic case, equilibrium equations can be written in terms of displacements and elastic constants. The solution for an isotropic material in which the particle motion is in the direction of propagation is

$$V_P = \left(\frac{C_{11}}{\rho}\right)^{1/2} = \left(\frac{\lambda+2\mu}{\rho}\right)^{1/2}\ .$$

The solution for the wave in which the particle motion is normal to the direction of propagation is

$$V_s = \left(\frac{C_{44}}{\rho}\right)^{1/2} = \left(\frac{\mu}{\rho}\right)^{1/2} .$$

The experimental program measures V_p, V_s, and ρ directly. From these measurements the elastic moduli are calculated

$$B = \rho\,(V_p^2 - 4/3\ V_s^2),\ G = \rho\ V_s^2,\ \nu = \frac{V_p^2 - 2V_s^2}{V_p^2 - V_s^2} , \qquad (1)$$

and

$$E = \frac{9\ B}{\frac{3B}{\rho V_s^2} + 1} . \qquad (2)$$

These acoustically determined moduli are referred to as determined moduli because they are computed from velocity data and not actually measured.

While the elasticity of the rocks is discussed above as if they were isotropic, neither their grain nor crack orientation is expected to be truly isotropic. The Westerly granite may be quite close to isotropic; the sedimentary limestone and sandstone are probably best described by a transverse plane of symmetry. As more data become available, the description can be further explored; present results show that the isotropic condition is a reasonable first approximation.

EXPERIMENTAL PROCEDURES

The elastic properties of the rocks are measured by two techniques. One technique, referred to as the static or volume method, uses strain gages mounted on the sides of a cylindrical sample or measures the displacement of a piston into a cylinder. The other technique, referred to as the dynamic or acoustic velocity method, determines the transit time of acoustic waves

through the sample. The acoustic and strain gage measurements were made simultaneously on the same sample as this was an objective of the experimental program. The piston-displacement experiment was used to extend the strain gage volume measurements to higher pressures.

Acoustic Method

Measurement of acoustic velocity in rock specimens at pressure was first described in detail by Birch.[2] In his method, the transit time of sound waves through the specimen is measured. Another signal is passed at one atmosphere through a material of known velocity (delay line) and the travel time between the two is matched. He calculated the velocity of sound in the specimen from the known velocity of sound in the delay line, the distance of travel in the delay line, and the distance of travel in the specimen.

This research also measures the velocity from travel time and distance. The present experimental setup is shown in Figure 2. The high-powered pulsed oscillator and the oscilloscope are triggered externally. The signal from the pulsed oscillator is sent to one transducer of the specimen and the oscilloscope. The received signal is amplified and sent to the other preamplifier of the oscilloscope. A time-mark generator provides a time base through a second channel on one of the preamplifiers of the oscilloscope. Thus, three traces are observed on the oscilloscope, the oscillator signal, the received signal, and the time-mark pulses (Figure 3).

An electric signal, due to pick-up in the wires that go through the high-pressure head, is observed at the beginning of the received signal. From the internal delay in the oscilloscope and the timing marks, the delay difference between the electric signal and the received pulse is measured to obtain the travel time in the specimen. The electric signal is delayed from

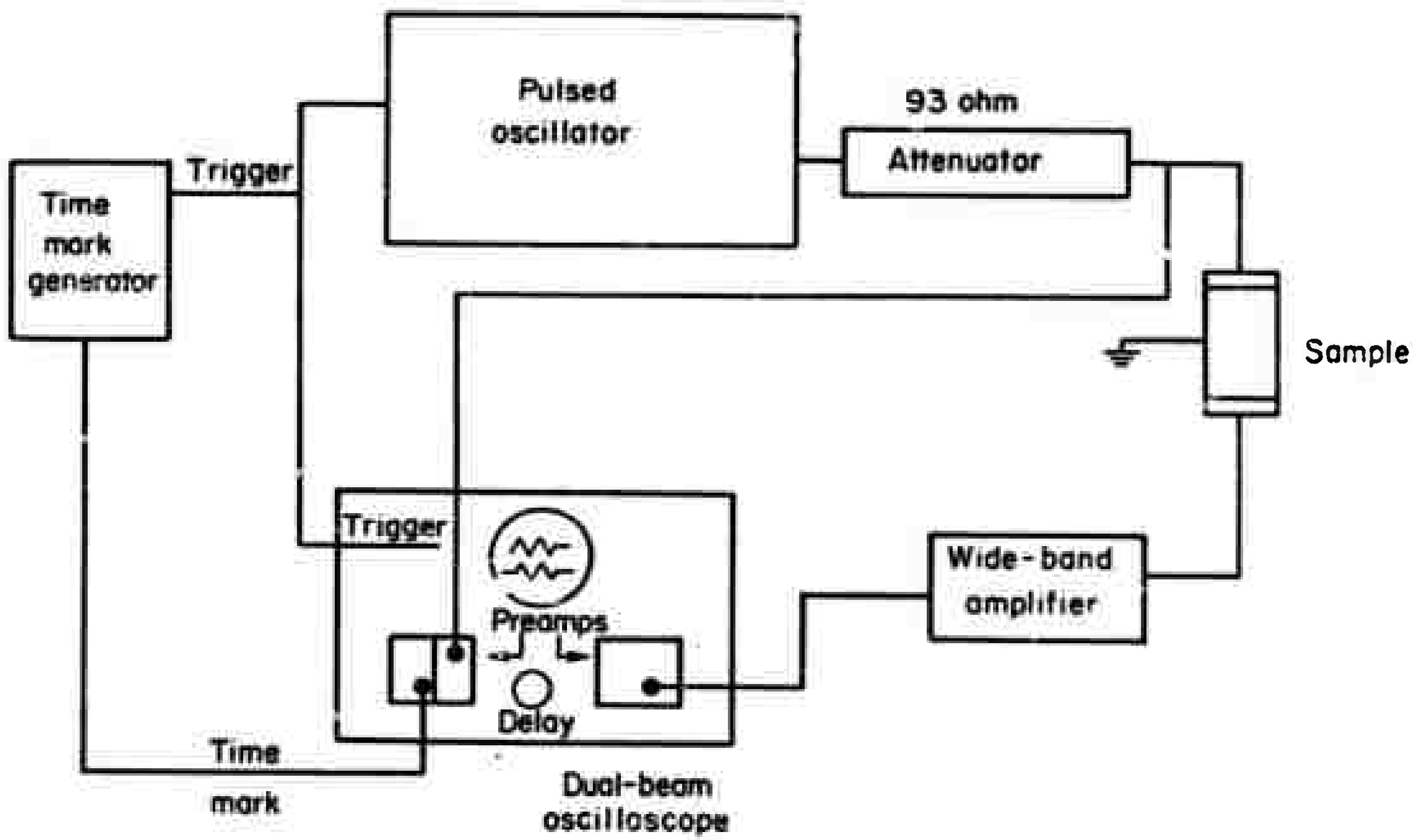


FIGURE 2. SCHEMATIC OF ULTRASONIC MEASUREMENT

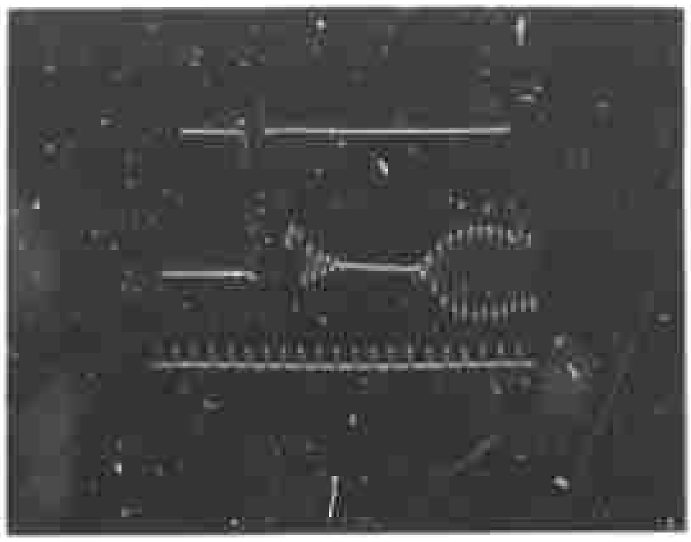


FIGURE 3. OSCILLOSCOPE TRACES OF ULTRASONIC EXPERIMENT IN SALEM LIMESTONE (PRESSURE = 600 BARS)

Top Trace - Initial Pulse
Middle Trace - Received Signal
Bottom Trace - 1 μsec Time Marks

the initial pulse by a certain system delay. By measuring the travel time in a series of samples of different lengths, system delay for a sample of zero length has been determined to be 0.55 microsecond.

The delay line in the oscilloscope is used only to divide up the difference between the one-microsecond timing marks. Thus, a few percent error in the oscilloscope delay line results in only a few tenths of a percent error in velocity. Since the velocities determined by travel times are generally accurate to 1 percent, any error resulting from the oscilloscope delay line is unimportant. A 1 percent accuracy in velocity leads to accuracies of approximately 2, 6, 8, and 10 percent in shear modulus, bulk modulus, Poisson's ratio, and Young's modulus, respectively.

Figure 4 shows our sample configuration. The assembly shown in Figure 5 is essentially the same as pictured in Figure 4 except for the BNC end connections. The assembly shown in Figure 4 has been used exclusively during the present research. These assemblies were developed during the early stages of the program; details of mounting the copper jackets and strain gages are given in the next section.

A previously used configuration was found unsatisfactory for the present experiments because the Westcoat amber used to coat the sample and prevent fluid intrusion had to be applied at 350 F (this was deemed undesirable) and reacted with the pressure fluid over the long times required for the experiments.

The biggest difficulty in designing the new assembly came in finding a potting material for the end pieces which would be soft and not react with the pressure fluid. A RTV polysulfide rubber material (Eccobond 2C) has been found satisfactory in all requirements. The material has a 450 psi tensile strength and transmits pressure quite hydrostatically.

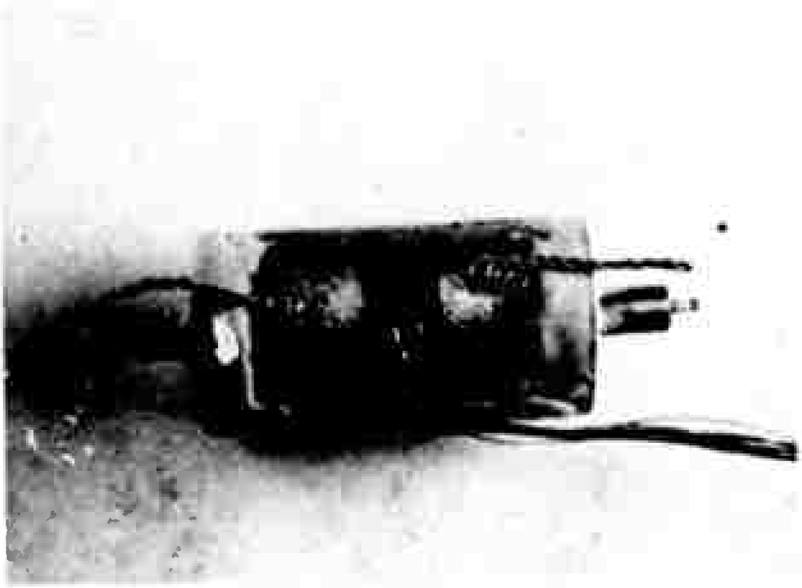


FIGURE 4. SAMPLE ASSEMBLY FOR SIMULTANEOUS ULTRASONIC AND VOLUME MEASUREMENTS ON ROCKS

Polysulfide rubber end seals and seal along copper seam are shown. Braided wire is the ground; round pieces from both ends are the copper electrodes. Radial strain gage is shown. Pockmarks are due to porosity in sample.

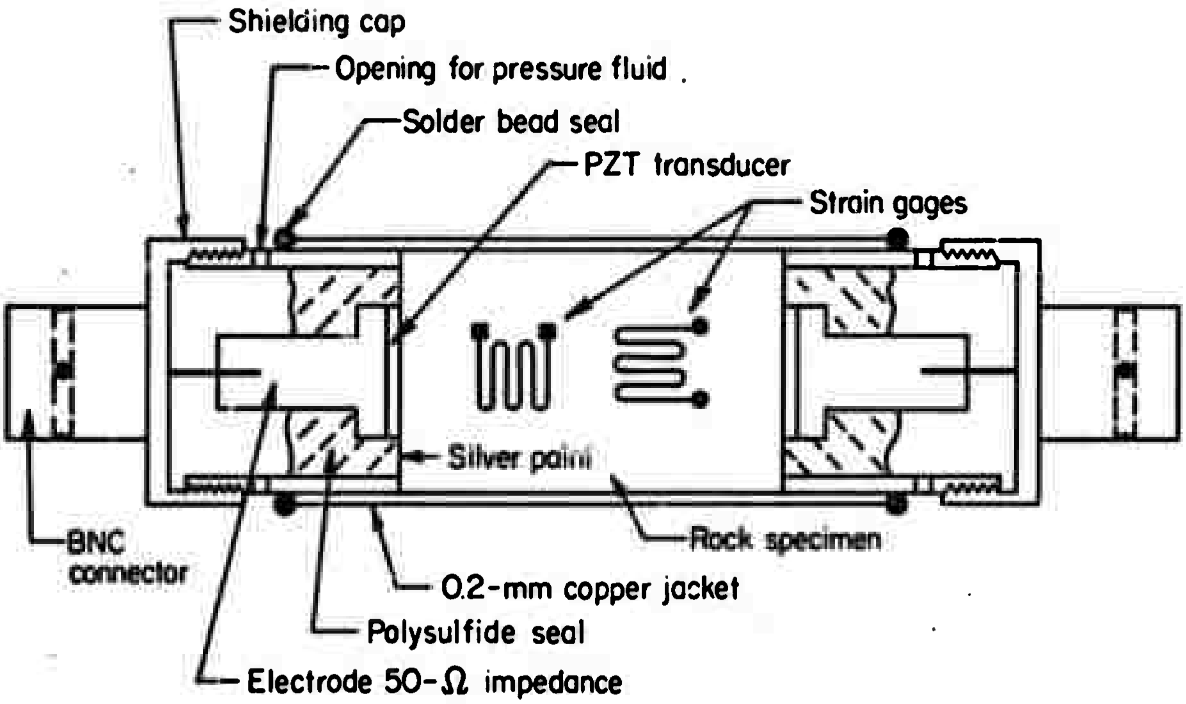


FIGURE 5. SAMPLE ASSEMBLY FOR ULTRASONIC AND VOLUME HIGH PRESSURE EXPERIMENT WITH NO ELECTRIC PICKUP

The sample assembly in Figure 5 is an improved version of that in Figure 4. A special feature of this sample design is the electrodes which have been designed with 50-ohm impedance to the outside copper jacket. It has no electric pick-up at the frequencies (one MHz) of the experiment. At one atmosphere, this assembly has given observable pulse-echo signals in Salem limestone and Westerly granite. A new high-pressure closure assembly was designed to prevent any electric pick-up in the sending or receiving of signals. This improvement in the experimental technique is exciting because it could enable shear and compression velocity measurements on the same sample in the high-pressure environment. This new approach will be used in future work.

Coupling of the shear-wave transducer to the sample is a problem because of the high-pressure environment. The usual cementation of the transducer to the specimen often results in a broken transducer after excursion to high pressure. While the desired velocity measurements are usually obtained, it is undesirable because of the continued breakage of transducers. Experimentation with several materials following a suggestion by Schock[8] has led to high-viscosity polystyrene resins, available from several manufacturers, that will transmit the shear wave satisfactorily and still not cause transducer failure in the high-pressure environment. Resins with viscosity of approximately 10,000 centipoises have worked satisfactorily.

Volume Methods

Strain Gages

In this technique the 25.4-mm diameter x approximately 40.0-mm-long samples are enclosed in a 0.2-mm-thick copper jacket. The jacketed virgin

samples are hydrostatically pressurized to about 100 bars in order to test the integrity of the copper jacket and to shrink the jacket onto the sample. If the copper jacket leaks, the fluid seeps into the pores of the rock. This is detected by noticing a change in the weight of the rock plus the jacket. While the pressurization results in some uncertainty in the low-pressure compressibility measurements, it is required for the present technique. Experience indicates that the rocks are elastic in this range.

Two perpendicular gages are mounted on the copper-jacketed rock samples (see Figures 4 and 5). By mounting the strain gages axially and circumferentially around the sample, it is possible to measure the linear compressibility in one direction and circumferential strain and thus determine the difference in compressibility of the sample in two directions. Ideally, this should be done on three mutually perpendicular samples but for the present experiments this has not been done. Compression is calculated from $\Delta V = \Delta L$ axial + 2 ΔL radial. This approach in effect accounts for transverse symmetry.

Two sizes of strain gages have been used: 6.2 and 12.7-mm square. The small grain size and the quality of the specimens used in this program allow either gage to statistically sample the strain in the rock. Void spaces, which are a result of the high porosity in the limestone and sandstone, occur under the strain gages and cause indentations. The experiments show that these void spaces do not have a noticeable effect on the accuracy of the experiments except when the gage breaks due to a large amount of strain across the corner of the indentation. This results in easily identified and discarded erroneous points. Gage failure on the limestone has been about 10 percent but the sandstone has shown 100 percent failure across the bedding plane at pressures below 4 kb for dry samples. Strain gages on water-filled Berea sandstone samples do not fail more than is normally expected.

In these experiments the compressibility of the rocks is measured in relation to that of a standard in order to correct for the effects of pressure on the gage factor of the strain gages, the effect of the mounting material, and the effect of curvature on the circumferential strain gage. This last effect is important.[6] The correction factors for the two gages are: $\frac{\Delta L}{L_o}$ axial strain gage = - 2.34 x 10^{-7} per bar and the circumferential gage has a value of - 3.10 x 10^{-7} per bar + 5.41 x 10^{-12} per bar^2.

During the experimental program the crushing mode of failure or "crush-up" was observed in the sandstone and limestone. When this occurred the larger pores and voids (as opposed to thin cracks) collapsed due to failure of the solid material surrounding them. Crush-up occurred over a range of pressure and was incomplete at the highest pressure available (9 kb) in the hydrostatic apparatus.

Piston-Cylinder Method

Compressibility at higher pressures was examined in the piston-cylinder apparatus. In this experiment the sample is surrounded with a solid of low shear strength which acts as a hydrostatic pressure medium. Displacement of the piston is measured and compared with that of a known solid, usually iron. From this it is possible to calculate the compressibility of the unknown

$$\left(\frac{\Delta V}{V_o}\right)_{\text{unknown}} = \left[\left(\frac{\Delta L}{L_o}\right)_{\text{experiment}} - \left(\frac{\Delta L}{L_o}\right)_{\text{iron}}\right] \times \left.\frac{\text{Area}}{V_o}\right]_{\text{sample}} + \left(\frac{\Delta V}{V_o}\right)_{\text{iron}} . \quad (3)$$

This is quite straightforward if all parts of the experiment are constant except the sample material, i.e., unknown or iron.

The usual pressure medium is lead. Use of lead is a compromise as it permits the experiment to reach 40 kb but has low accuracy at pressures less than 2 kb. For the present experiments indium was the confining

pressure medium. Indium limits the upper pressure to about 20 kb because it causes the pressure vessel to fail. However, it increases the low-pressure accuracy due to its low shear strength.

Water Saturation

The specimens were saturated by a technique similar to that described by Brace, et al.[11] The sample is placed in water in a vacuum chamber, the pressure reduced, and the water is allowed to intrude into the sample. The sample is then placed in a water filled-air free container and placed overnight at 1200-1500 psi. The sample is weighed and the pressure treatment is repeated until two weighings are the same.

The saturated rock specimen is then prepared for the velocity and strain measurements in the manner described above. Thus the pore pressure was not constant during the experiment because (1) the water was confined and (2) no water was added. This approach gives a realistic situation to what one would encounter in an excavation process where the amount and location of the water would probably remain constant during fast pressurization.

Cyclic Loading

Cyclic loading was accomplished by repeatedly reloading a sample to the same or higher pressures, e.g., 0 kb to 1 kb to 0 kb to 3 kb to, etc. Our shorthand notation for this is 0-1-0-3- etc. kb. The purpose of this cyclic loading was to simulate repetitive loadings that rocks are often subjected to in excavation processes, e.g., drilling, blasting, and tunnelling. The objective was to determine how the elastic properties change with repeated stressing.

Samples

The rock samples used in this program came from oriented samples of Salem limestone and Berea sandstone collected by the author and Westerly granite collected by the U. S. Bureau of Mines. Each of these samples was collected as a single piece in an amount sufficient to cut forty 1-foot cubes. The cubes were numbered so as to identify their location in the large block. The large blocks were oriented as to in situ top and bottom; magnetic north was also determined for the Westerly granite. Specific details on the oriented blocks as well as detailed physical properties will be available in a publication from the U. S. Bureau of Mines.

Table 1 gives information as to the location of samples used in the experiments. The first designation in the sample I.D. is the block number, the second is the location within the block, and the third is the sample number. Figure 6 shows the location identification system we use. x = 0, y = 0, z = 0 all start from the bottom left-hand corner of the block when the observer looks at the block identification number right side up with the number on the top. Block 2A of the Westerly granite was received as a 6 x 6 x 6-inch cube. South makes an angle of 33.8 degrees from the x axis in the plus x, y quadrant.

EXPERIMENTAL RESULTS

Data Analysis

Acoustic Velocity and Strain Gage Experiment

Acoustic velocity and linear strain versus pressure were obtained for the Salem limestone, Berea sandstone, and Westerly granite. The

TABLE 1. SAMPLE CYLINDER LOCATIONS FROM LARGE BLOCKS

Experiment	Sample	Sample I. D.	Position
1025-4	Salem limestone	29-B-12	4-5/8 z, 5 x, 0 - 1-11/16 y
1025-9	Salem limestone	29-B-16	6-9/16 z, 4-1/8 x, 2-1/16 - 4 y
1025-10	Berea sandstone	40-H1-G	11-3/8 x, 1-15/16 y, 7-1/2 - 9 z
1025-11	Berea sandstone	40-H1-E	11-3/8 x, 3-5/8 y, 7-1/2 - 9 z
1025-13	Salem limestone	29-B-13	4-5/8 z, 5-1/8 x, 2-1/16 - 4 y
1025-18	Salem limestone	29-B-19	6-13/16 z, 3-9/16 x, 4 - 6 y
1025-19	Berea sandstone	40-E-6	8-1/2 x, 4-7/8 y, 4 - 5-3/4 z
1025-21	Salem limestone	29-B-8	7-3/4 z, 5 x, 0 - 1-11/16 y
1025-22	Berea sandstone	40-E-2	9 x, 7-3/8 y, 4 - 5-3/4 z
1025-23	Westerly granite	5-2A-2	4.2 x, 0.6 z, 0 - 2 y
1025-24	Westerly granite	5-2A-3	3.1 x, .65 z, 0 - 2 y
1025-25	Berea sandstone	40-E-5	9 x, 5-7/8 y, 4 - 5-3/4 z

experimentally measured parameters were the travel time of the acoustic wave through the specimen, the change in resistance of the strain gages, and the change in resistance of the manganin pressure cell. The measured experimental quantities were converted to pressure versus linear strain, volume strain, and velocity by means of a special computer program, EOS2, developed for this research program. This program and the tabulated data for all the experiments that gave useful results are given in Appendix I. The program uses a quick plot subroutine (not shown) which plots the data. Selected plots from the volume data are given in Appendix II.

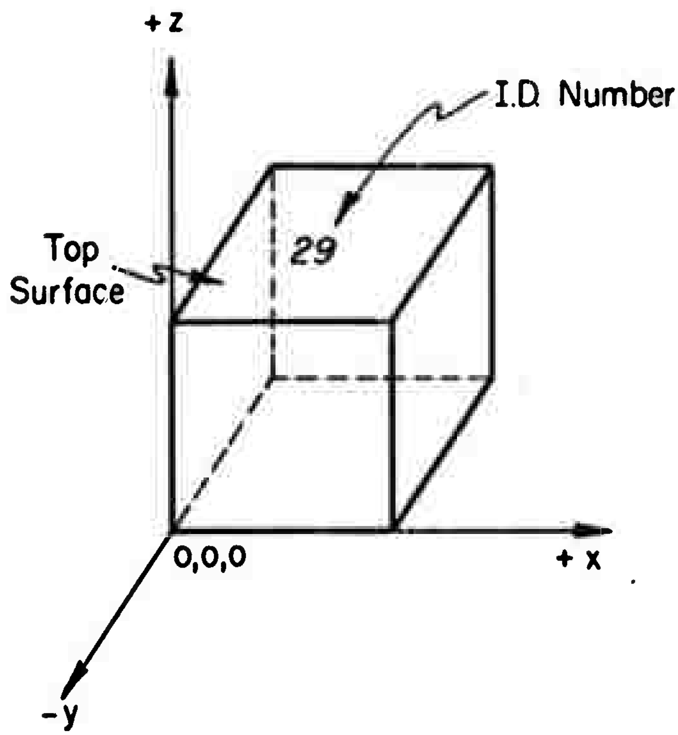


FIGURE 6. SAMPLE ORIENTATION IN ORIGINAL BLOCK

The velocity and specific volume data from EOS2 were determined at specific pressures to obtain the dynamic elastic moduli. These data were used as input into a second program, DYNMOD, which calculated the dynamic elastic moduli as shown in Equations (1) and (2), as well as

$$\text{Lamé constant } \lambda = \rho\,(V_p^2 - 2V_s^2)$$

$$\text{Seismic Parameter } \phi = V_p^2 - 4/3\, V_s^2$$

$$\text{Bulk Velocity } V_B = [\phi]^{1/2}$$

$$\text{Mean Velocity } V_m = \left(\frac{2}{3V_s^3} + \frac{1}{3V_p^3}\right)^{-1/3}$$

$$\text{Debye Theta } \theta_D = 231.3\,(\rho/\bar{M})^{1/3}\, V_m$$

$$\text{when } \bar{M} = \text{mean atomic weight per atom.}$$

The program and results are given in Appendix III.

The static bulk modulus was calculated by first fitting the pressure-volume data to one or more different polynominal curves. These were then differentiated to give the static bulk modulus. At times it was more convenient to differentiate the experimental data.

Piston-Cylinder Volume Experiment

Volume strain was measured in a piston-cylinder apparatus to extend the strain gage measurements to high pressures. The measured quantities, piston displacement, ram pressure, piston diameter, ram diameter, sample weight and dimensions were used to calculate pressure versus volume by means of Equation (3).

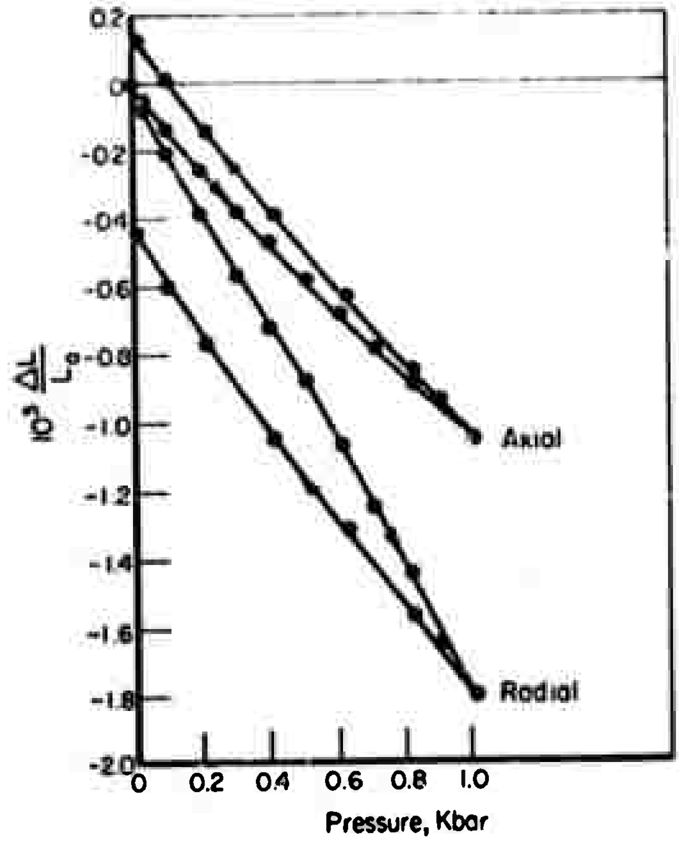
Detailed Results

The experimental results are most easily presented and discussed if the distinction is made between the dry and the water-filled samples as we have done below. The acoustic velocity and volume results are presented simultaneously for each rock type in order to make direct comparisons between the dynamic and static measurements, one of the stated goals of this research program. The effects of cycling loading are presented as they affect these results.

Dry Samples

Salem Limestone. The results of linear strain and velocity for dry Salem limestone, Figures 7, 8, and 9, are fairly representative of results on dry porous rock. The first compression cycle to any given pressure maximum is in agreement with information in the literature. The volume measurements associated with the crush-up represent new data as do the effects of cycling on both the velocity and volume data.

In Figure 7 we see a large increase in velocity at low pressures as well as a large $\Delta L/L_o$. Both effects are due to the closing of thin cracks. This figure also shows that the rock has experienced permanent changes at this low pressure. The results of the next cycle, to 5 kb, are shown in Figure 8. In this cycle the strain gages show greatly increased length changes in the 2 to 5-kb region and exhibit on release greater than 1 percent permanent decrease in length. This is caused by the sample crushing up or the crushing mode of failure. It is clear that at 5 kb the limestone has not finished this crush up. No such profound change occurs in the velocity curve. A bump appears in the velocity curve. All of our data show a bump in the velocity versus pressure curves near the start of the crush up. In Figure 9 we see that this occurs on the next cycle near 5 kb. The $\Delta L/L_o$ data show



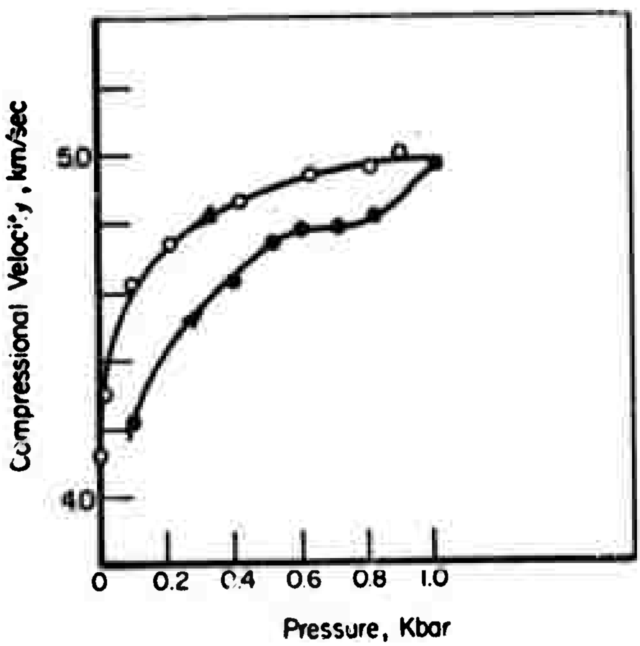
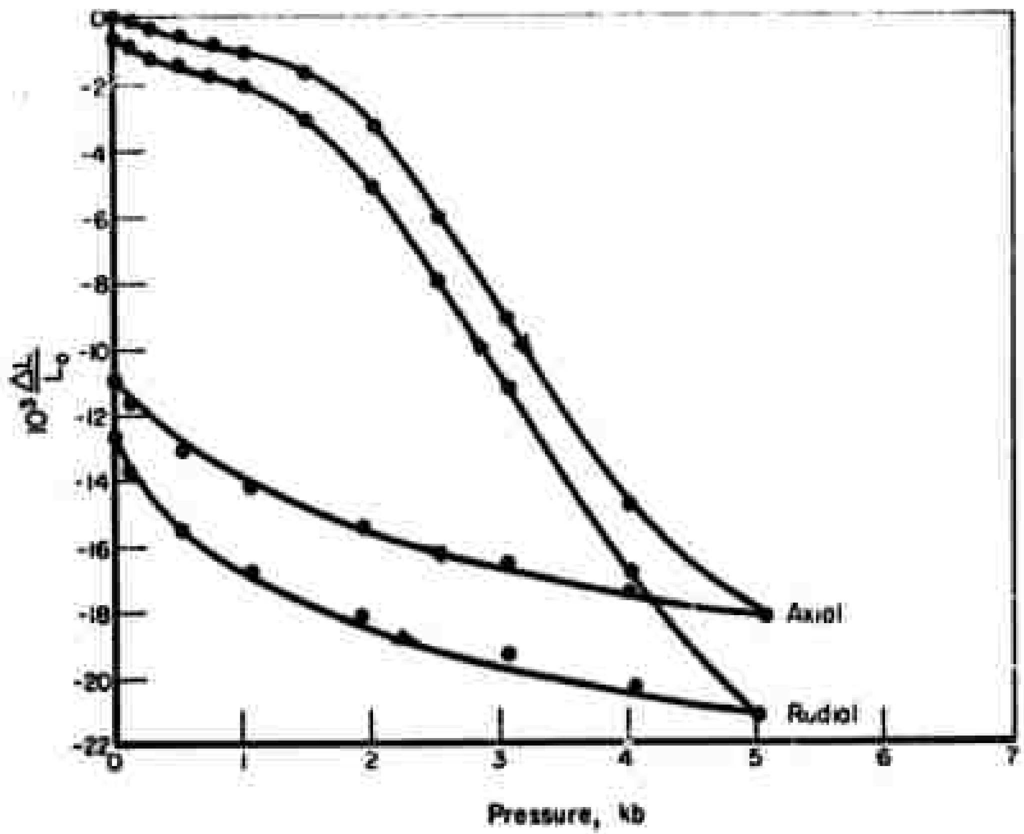


FIGURE 7. SALEM LIMESTONE, DRY (1-KBAR CYCLE)



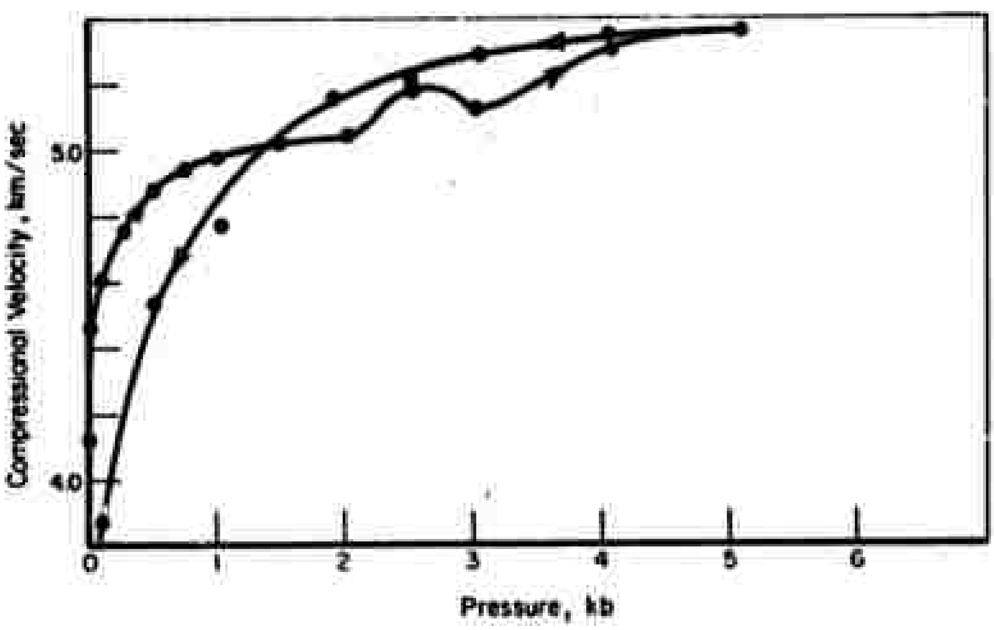


FIGURE 8. SALEM LIMESTONE, DRY (5-KBAR CYCLE)

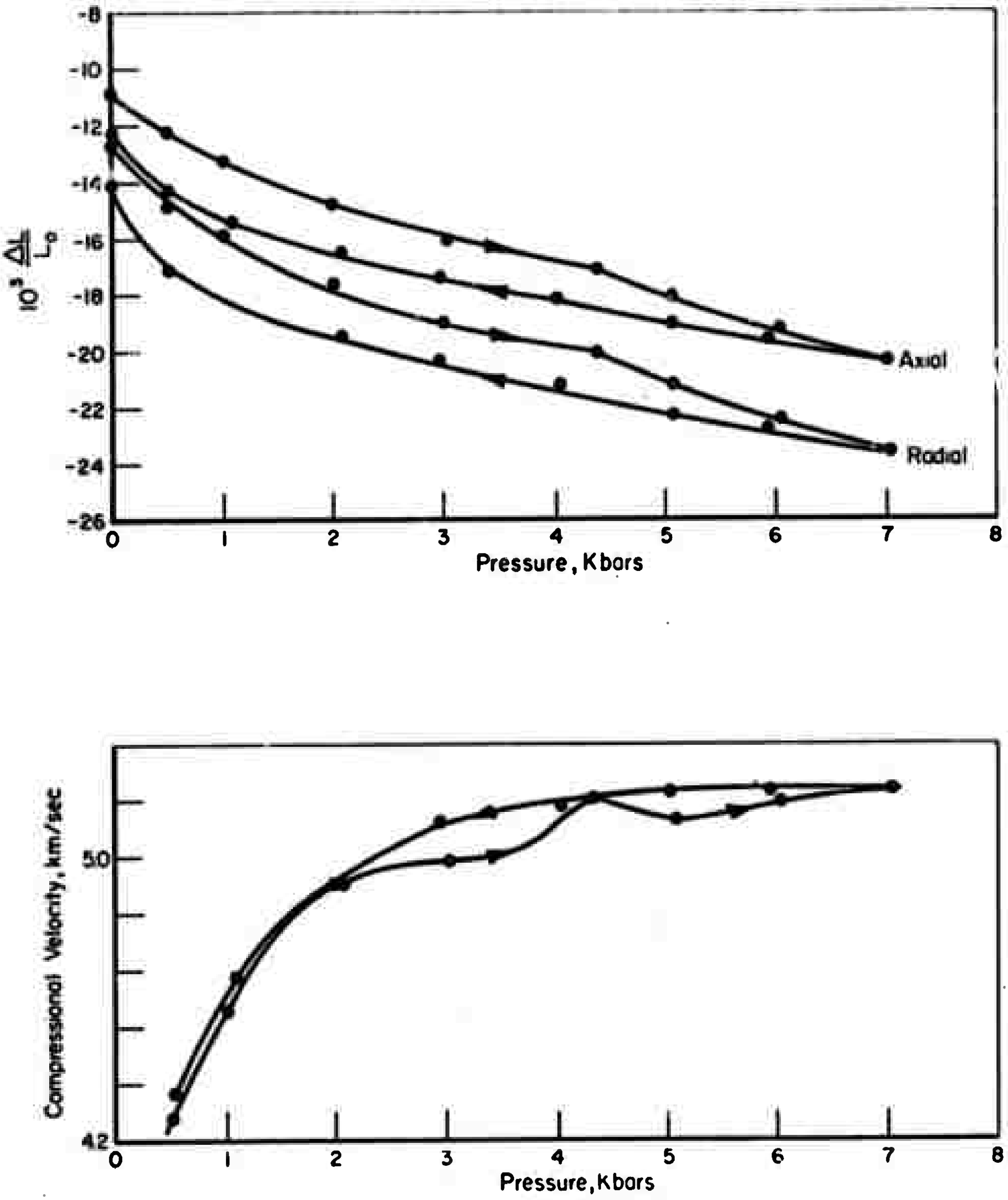


FIGURE 9. SALEM LIMESTONE, DRY (7-KBAR CYCLE)

an expected increase in compressibility as the limestone starts to continue the crush up at 5 kb, and as noted we have a concurrent bump in the velocity curve.

These figures indicate how pressure cycling changes the character of the sample. The larger pores are closed due to the initial crush up and create many new cracks. These new cracks have various height-to-length ratios. Since the height-to-length ratio controls the pressure of crack closure a much greater pressure interval will exist on subsequent cycles where the effects of the cracks are evident. The velocity data in Figure 9 suggest that it is at least 3 kb before the majority of the cracks close on subsequent cycles.

Figure 10 shows the bulk modulus of the Salem limestone from the strain gage measurements. Curves A, C, E are compression; B, D, and F, pressure release. The effect of the crushing mode of failure (under hydrostatic conditions) is clearly evidenced by the large decrease in modulus.

The static modulus is related to the derivative of $\Delta L / L_o$; the dynamic modulus is proportional to velocity squared. Thus the dynamic bulk modulus, in Figure 11, is similar to the velocity curves and not comparable to the volume bulk modulus. The overly pronounced knees in the velocity modulus in Figure 11 are caused by slightly different pressures of this effect occurring in the V_p and V_s data. This points to the importance of making all measurements at once. Note that at the start of the release curve F the static bulk modulus <u>is greater than</u> the dynamic.

Thin sections were made from both unpressurized Salem limestone and a sample which had crushed up, Figure 12. The unpressurized limestone contains distinct grains and void spaces (black in the photograph). The grains appear to be made up of submicroscopic subgrains. The complete grain often shows extinction under crossed nicols. Certain grains in the unpressurized sample contain distinct calcite twinning.

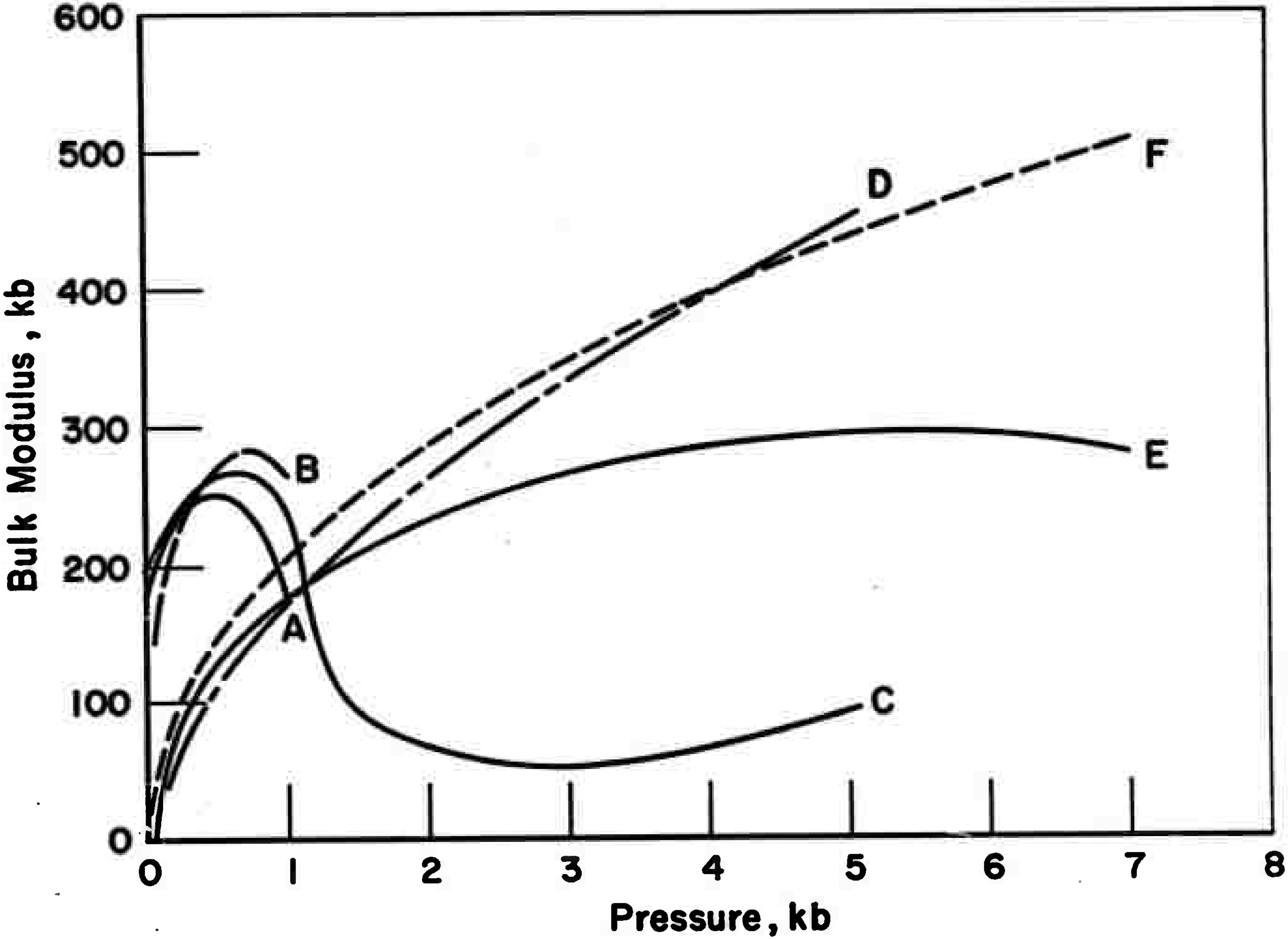


FIGURE 10. BULK MODULUS DRY SALEM LIMESTONE FROM VOLUME MEASUREMENTS CYCLED 0-1-0-5-0-7-0 KB

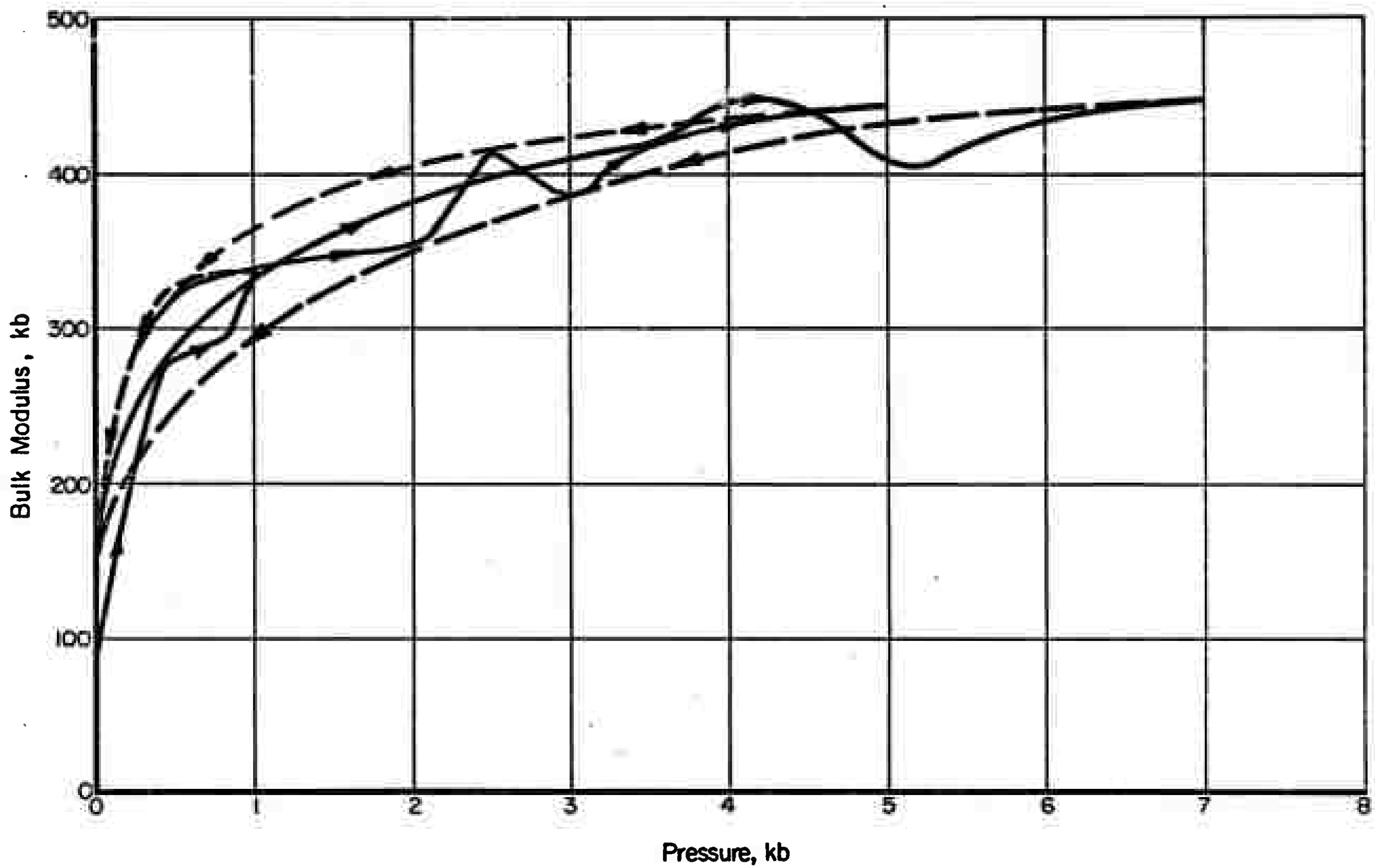
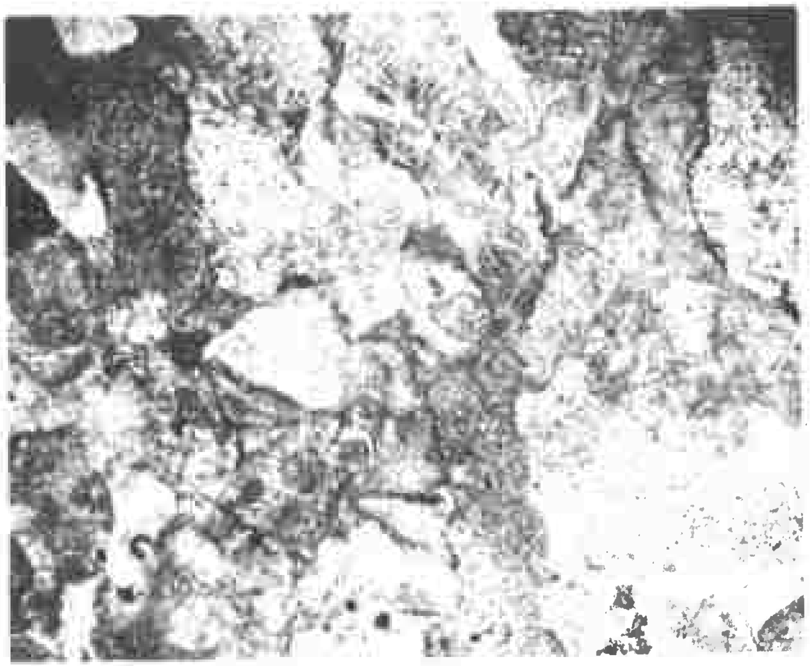


FIGURE 11. BULK MODULUS OF DRY SALEM LIMESTONE FROM ACOUSTIC VELOCITY EXPERIMENTS

50X

a. Crossed-Nicols, Unpressurized



50X

b. Crossed-Nicols, 7 Kb

FIGUR 12. SALEM LIMESTONE - THIN SECTIONS

This picture changes completely in the crushed sample. No void spots are evident, the distinct calcite twinning is gone or only a faint remnant remains, and the sample shows no distinct extinction. As the limestone rock crushes up, the individual grains move to fill in the void spaces. The grain boundaries are no longer straight. We know that at these confining pressures limestone deforms in a ductile manner.[9] However, in our experiments the individual grains are not stressed hydrostatically because of the porosity; fracturing occurs during crush up as is evidenced by the velocity data.

The Salem limestone reaches a specific volume of about 0.396 cc/g at 7 kb. This compares with 0.3688 cc/g for calcite at 1 atmosphere. Thus it is clear that even though the compressibility of the limestone is decreasing at the higher ranges of the strain gage experiment it should continue to crush up at still higher pressures. To examine this, the compressibility of the limestone was studied in the piston-cylinder apparatus to 16 kb. The results are shown in Figure 13. The experimental data are in Appendix IV. At 15 kb on the first cycle the limestone has reached 99 percent theoretical density. The next cycle shows about 99.4 percent at 15 kb. This is what one would expect for a material cycled to a pressure much greater than its brittle-ductile transition.

Berea Sandstone. The Berea sandstone reacts in manner similar to the Salem limestone except that the crushing mode of failure does not occur until 4.2 kb, Figures 14, 15, 16, and 17. This is due to the fact that quartz is a stronger material than calcite. The release velocity curve from the 5-kb cycle, Figure 15, shows a somewhat different result than that found in the similar experiment in the limestone, Figure 8. The release velocity curve for the sandstone immediately falls off and under the

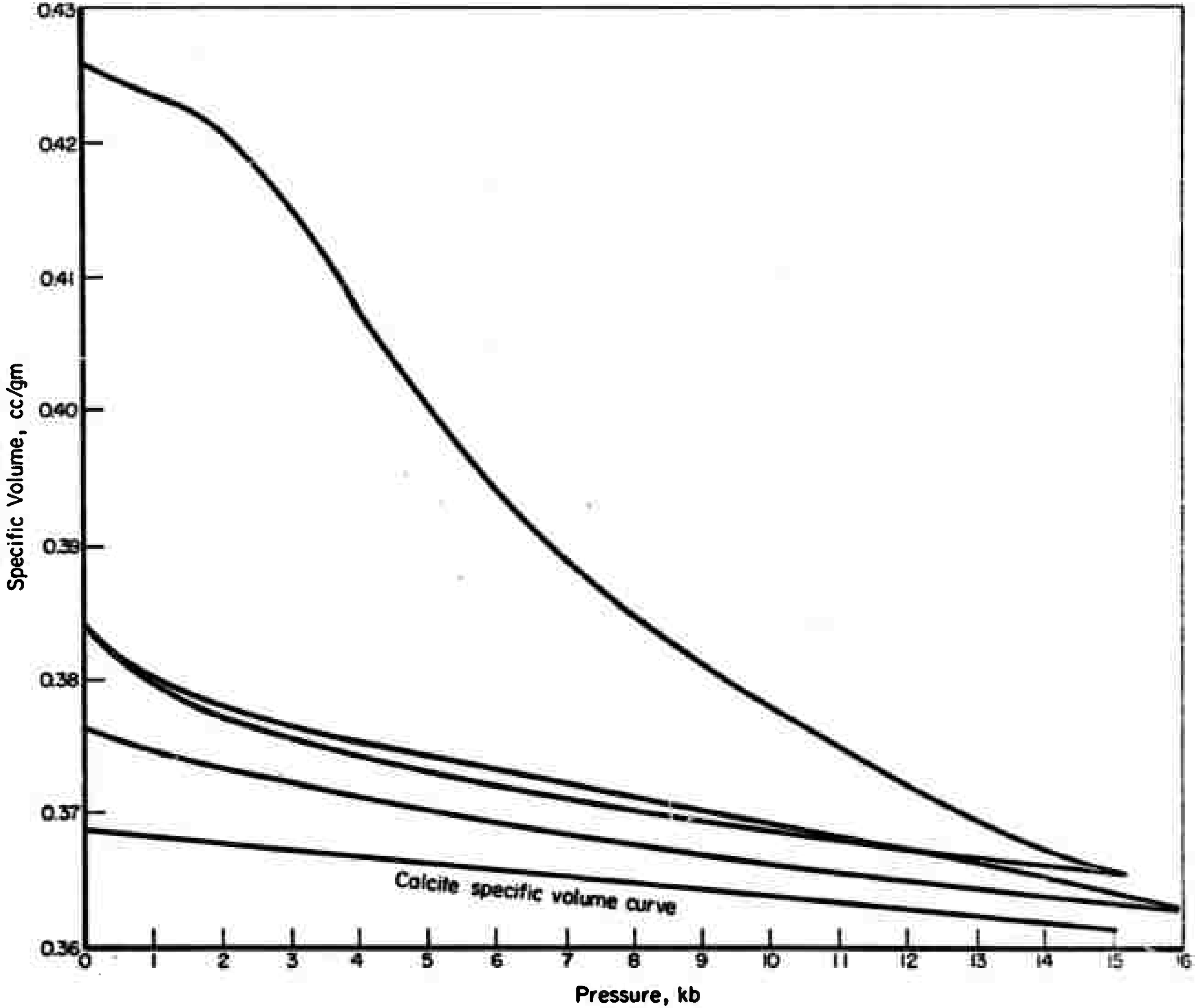


FIGURE 13. HIGH PRESSURE COMPRESSION OF SALEM LIMESTONE

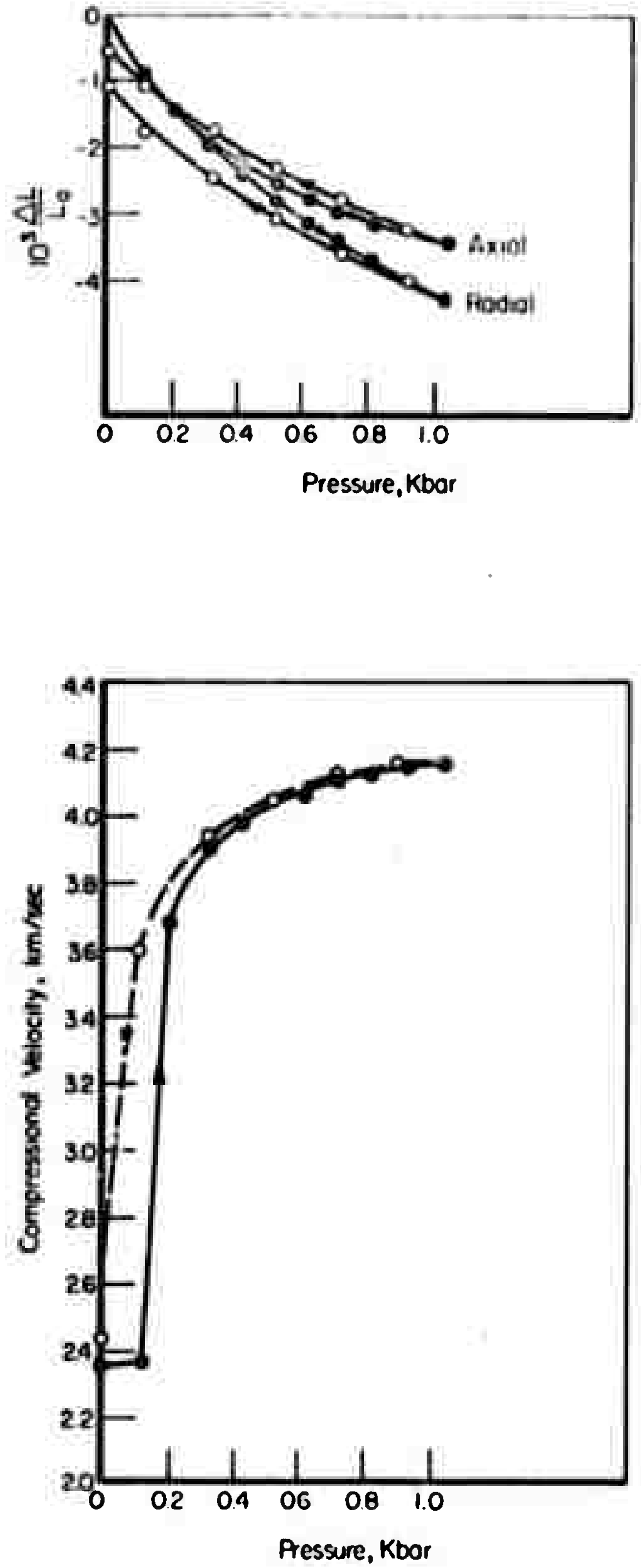


FIGURE 14. BEREA SANDSTONE, DRY (1-KBAR CYCLE)

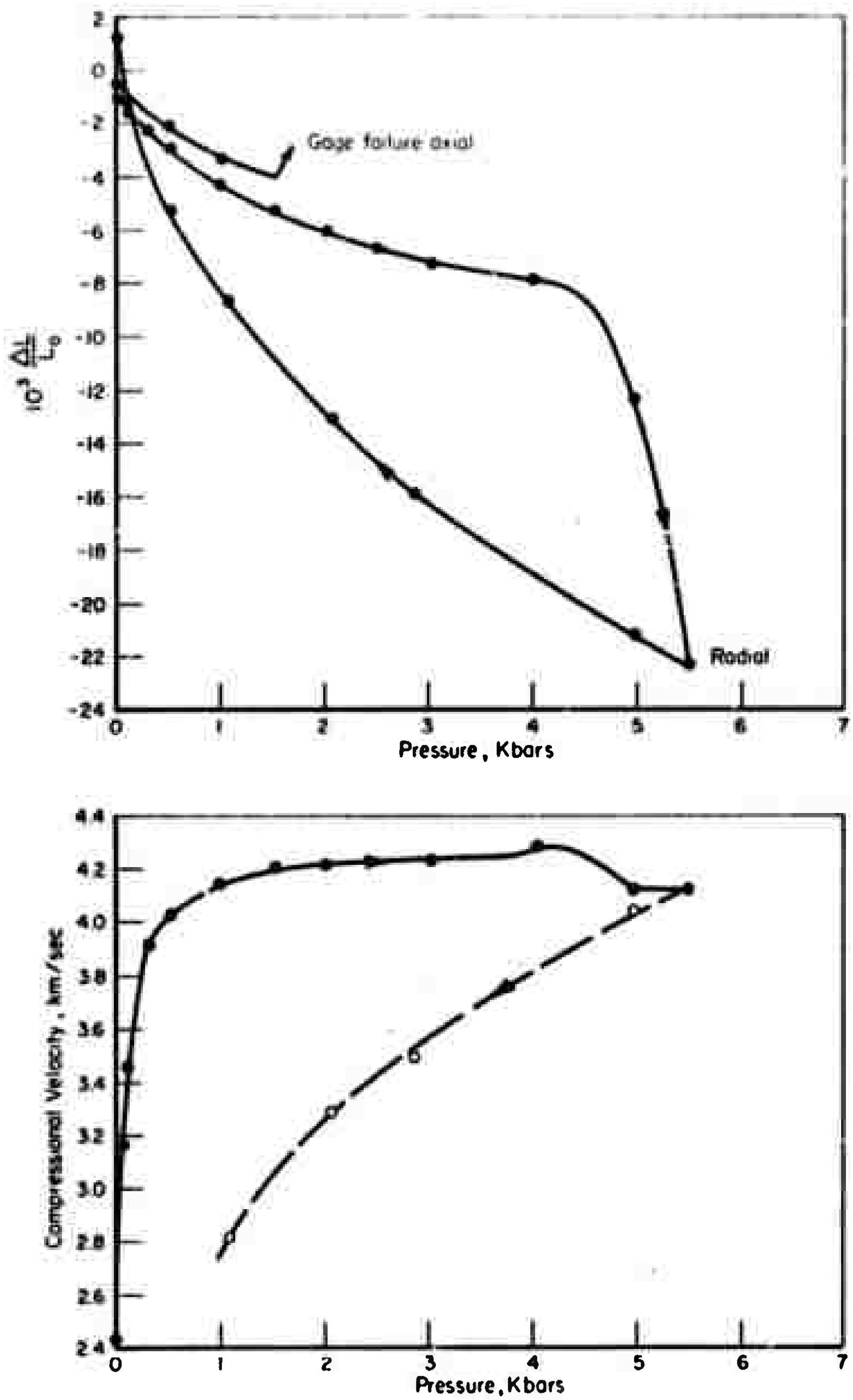


FIGURE 15. BEREA SANDSTONE, DRY (5-KBAR CYCLE)

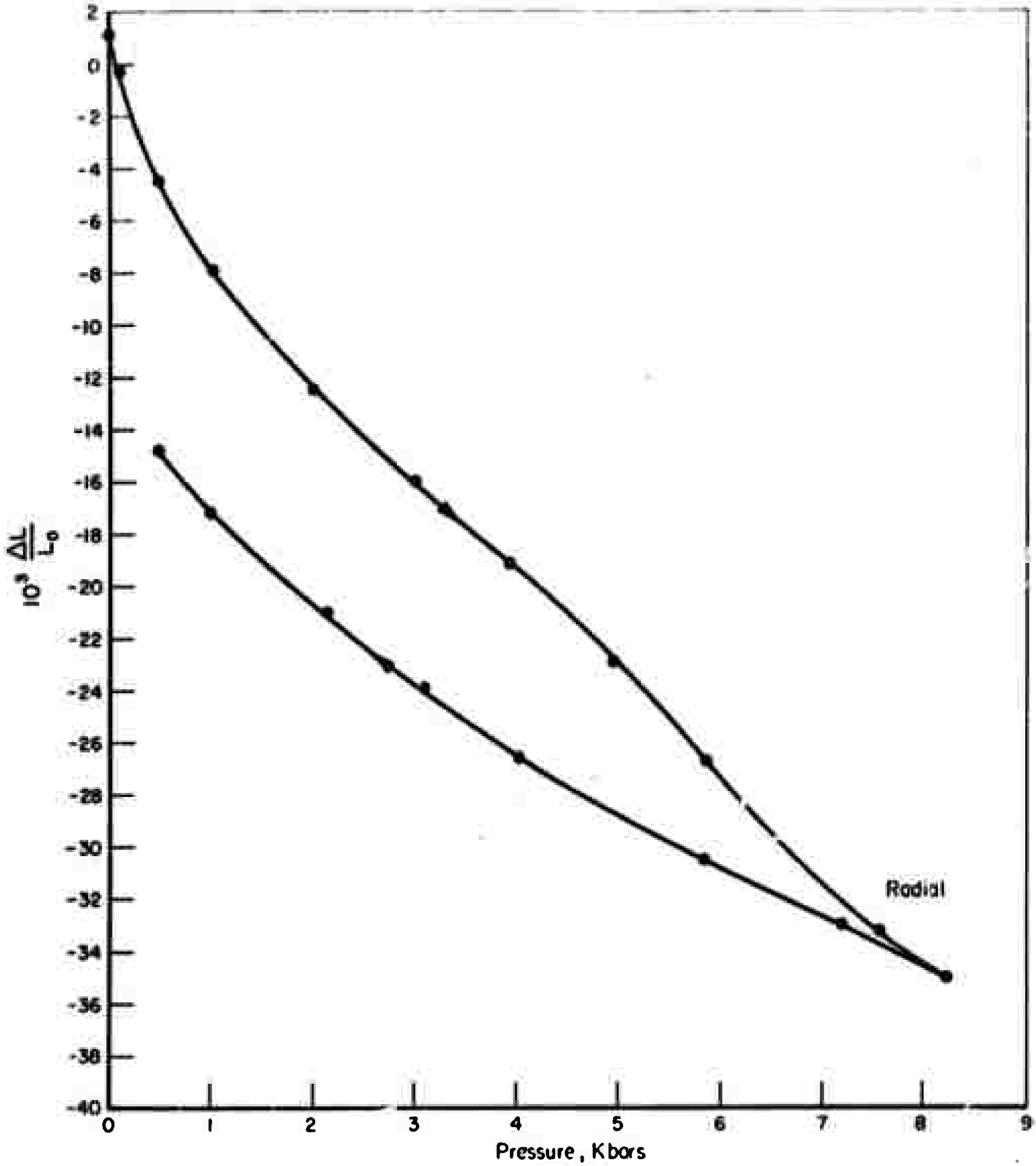


FIGURE 16. BEREA SANDSTONE, DRY (8-KBAR CYCLE)

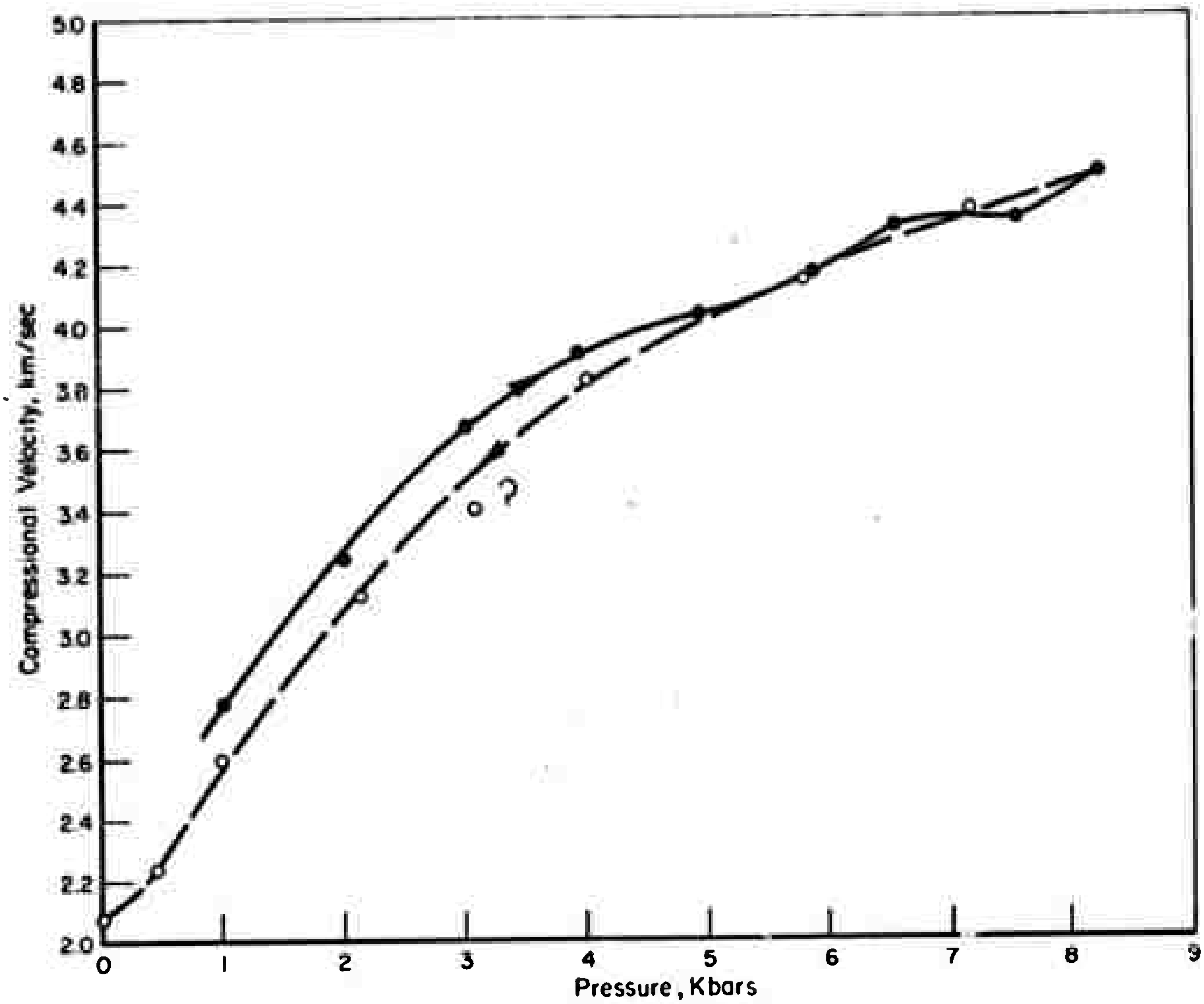


FIGURE 17. BEREA SANDSTONE, DRY (8-KBAR CYCLE)

compression curve while that of the limestone stays above the compression curve for several kilobars.

This effect is no doubt due to the difference in failure mechanisms of the calcite and quartz. The quartz grains in the sandstone fail by brittle fracture; the rock is deformed by cataclastic flow. The limestone is ductile at the confining pressures of the crush-up region.[9] When the pressure is released from the sandstone, the induced cracks open immediately causing a reduction in sound speed. Additional cycling, as shown in Figure 17, produces a similar effect although the compression velocity curve is influenced by the previous cycle. As the limestone, Figure 10, is in the ductile region, pressure release does not cause immediate crack opening.

In Figure 18 are microphotographs of thin sections of pressurized and virgin Berea sandstone. The unpressurized sandstone shows many void spaces (black areas in the thin section) and distinct separation of the quartz grains. The grains, appearing strain-free, show little undulose extinction and little or no cracking.

In the pressurized sample we see that the quartz grains have been pushed into intimate contact and the large void spaces removed. The quartz grains show cracking and fracturing; this fracturing has considerably reduced the size of many particles. In the center of the microphotograph we see one grain tip forced into another grain causing it to fracture. An increase in undulose extinction was evident. Comparison of this thin section with that of the limestone, Figure 12, is strong evidence for the explanation of the differences between their pressure-velocity curves after the occurrence of crush up.

Figures 19 and 20 are plots of the bulk modulus from the volume and velocity data. In the volume experiment curve C is based on data from both

150X

a. Crossed-Nicols, Unpressurized

155X

b. Crossed-Nicols, 8 Kb

FIGURE 18. BEREA SANDSTONE - THIN SECTIONS

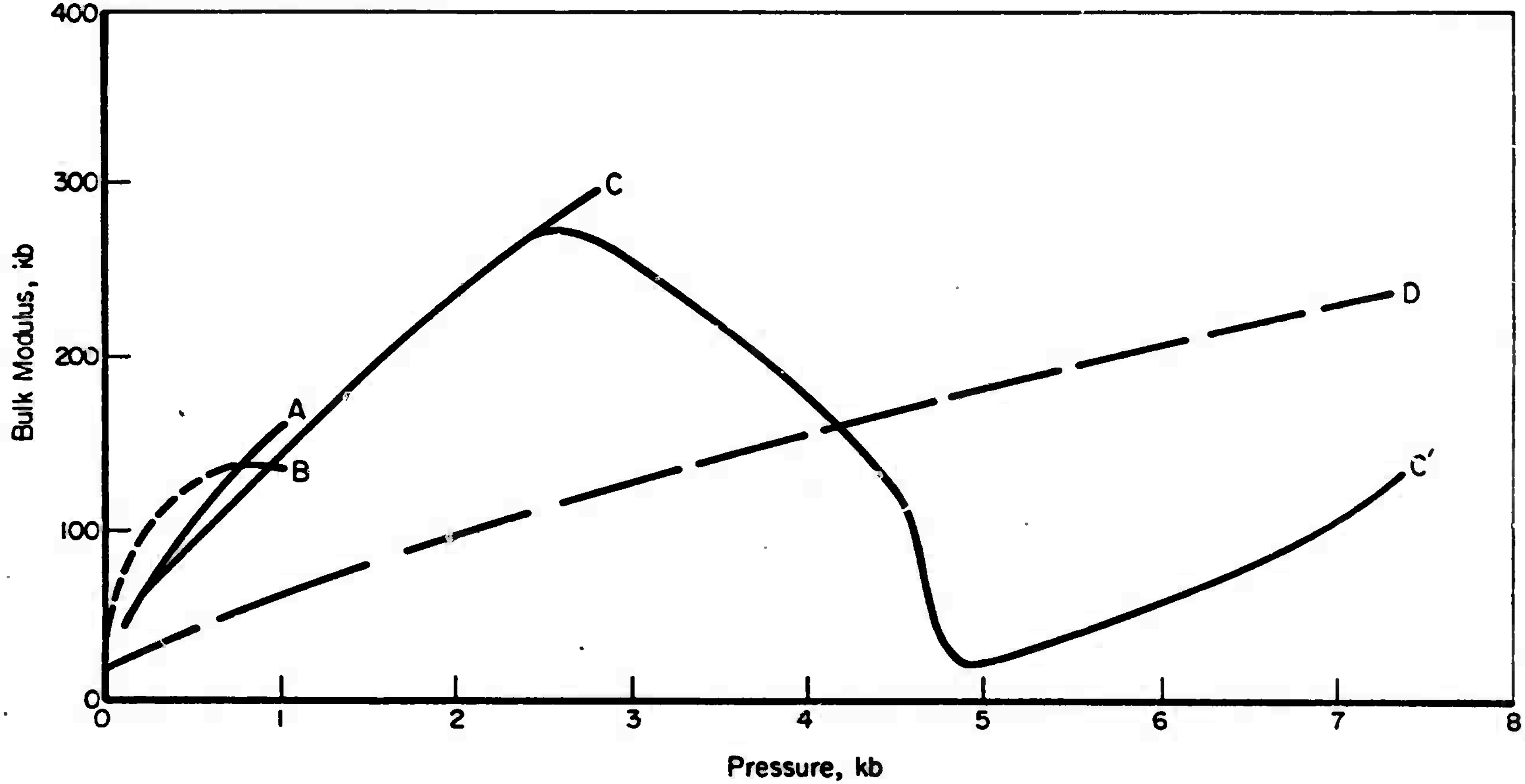


FIGURE 19. BULK MODULUS OF BEREA SANDSTONE FROM STRAIN GAGE MEASUREMENTS

Curves A, C compression; B, D release.

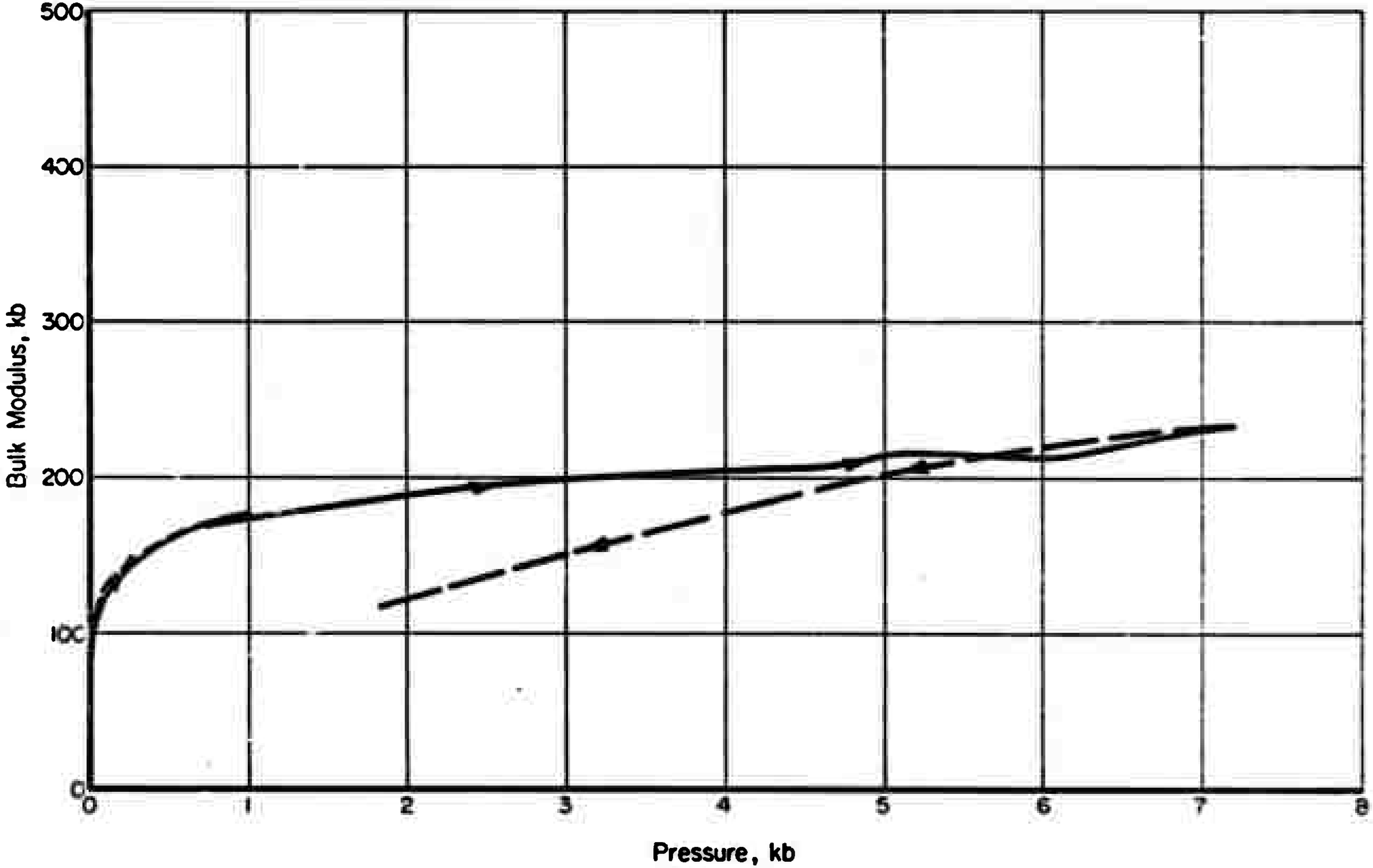


FIGURE 20. BULK MODULUS OF DRY BEREA SANDSTONE FROM ACOUSTIC VELOCITY MEASUREMENTS

strain gages, curve C^1 on only the radial strain gage after the failure of the axial strain gage.

Several important points concerning the relationship between the acoustic and volume bulk moduli are evident in these plots. At about 1.3 kb the volume bulk modulus becomes greater than that from the velocity determination and remains so until the crush up reduces it. Theory predicts that the volume bulk modulus should always be less than the acoustically determined bulk modulus

$$B_T = B_S \left(1 - \frac{T \alpha^2 B_T}{\rho C_p}\right) ,$$

(where T is temperature, α is thermal expansion and C_p is specific heat) and all experimental results on rock to date have shown this with the two exceptions found in this work. We believe that this observation on the Berea sandstone can be explained by the results of Borg, et al[(10)], on the experimental deformation of St. Peter sand. Their results indicate that even at low confining pressures of 1 kb the quartz grains can fracture. In the experiments on the St. Peter's sand, as well as our experiments with Berea sandstone, a porous material with rounded to subangular grains is stressed. These grains are in point contact and a small confining pressure will result in a high pressure at the contacts. Thus the grains fracture quite readily.

From the bulk modulus data shown in Figures 19 and 20 we deduce that fracturing is occurring at low confining pressures and this affects the velocity values and keeps them low. On the other hand, this fracturing is not sufficient to decrease the static bulk modulus below the dynamic until considerably higher pressure. However, the strain gages are sensitive enough to observe a decrease before the catastrophic crushing mode of failure occurs at 4.3 kb, Figures 15 and 19.

In this experiment, as with the limestone, note that the volume bulk modulus is greater at the start of pressure release than that determined from the velocities.

Westerly Granite. The results for dry Westerly granite are incomplete inasmuch as a shear velocity measurement has not been made. In general, the first compression results on linear strain and compressional velocity agree with the published values of Birch(2), Simmons and Brace(4), Schock, et al(12), and others.

Compressional velocity data are plotted in Figure 21. The velocity for the 3 and 9-kb cycles are lower than for the 1-kb cycle. This is apparently related to a slight permanent volume decrease associated with the 3-kb cycle We can see this better in the plot of bulk modulus from volume measurements, Figure 22. The 1-kb cycle and the initial part of the 3-kb cycle are reasonably close; after the excursion to 3 kb the bulk modulus is increased and the data no longer coincide with the previous cycles. The compression data, Appendix I, EXP 1025-23, show a slight permanent volume decrease. What apparently is happening here is an accommodation of the rock structure to the hydrostatic pressure by a slight volume decrease accompanied by a small increase in crack density as shown by the decreased sound speeds at low pressures.

Water-Filled Samples

The major effect of water is to decrease the compressibility, especially in the more porous rock, e.g., limestone and sandstone. However, the velocity values are increased due to increased transmission ability, quite like that found by Nur and Simmons.(14) Another important effect in highly porous materials like the limestone and sandstone is that the difference in compressibility between the rock and the water will cause a decrease in the pore pressure relative to confining pressure as long as the structural network of the rock remains intact. This will effectively make available a crush-up volume at some pressure.

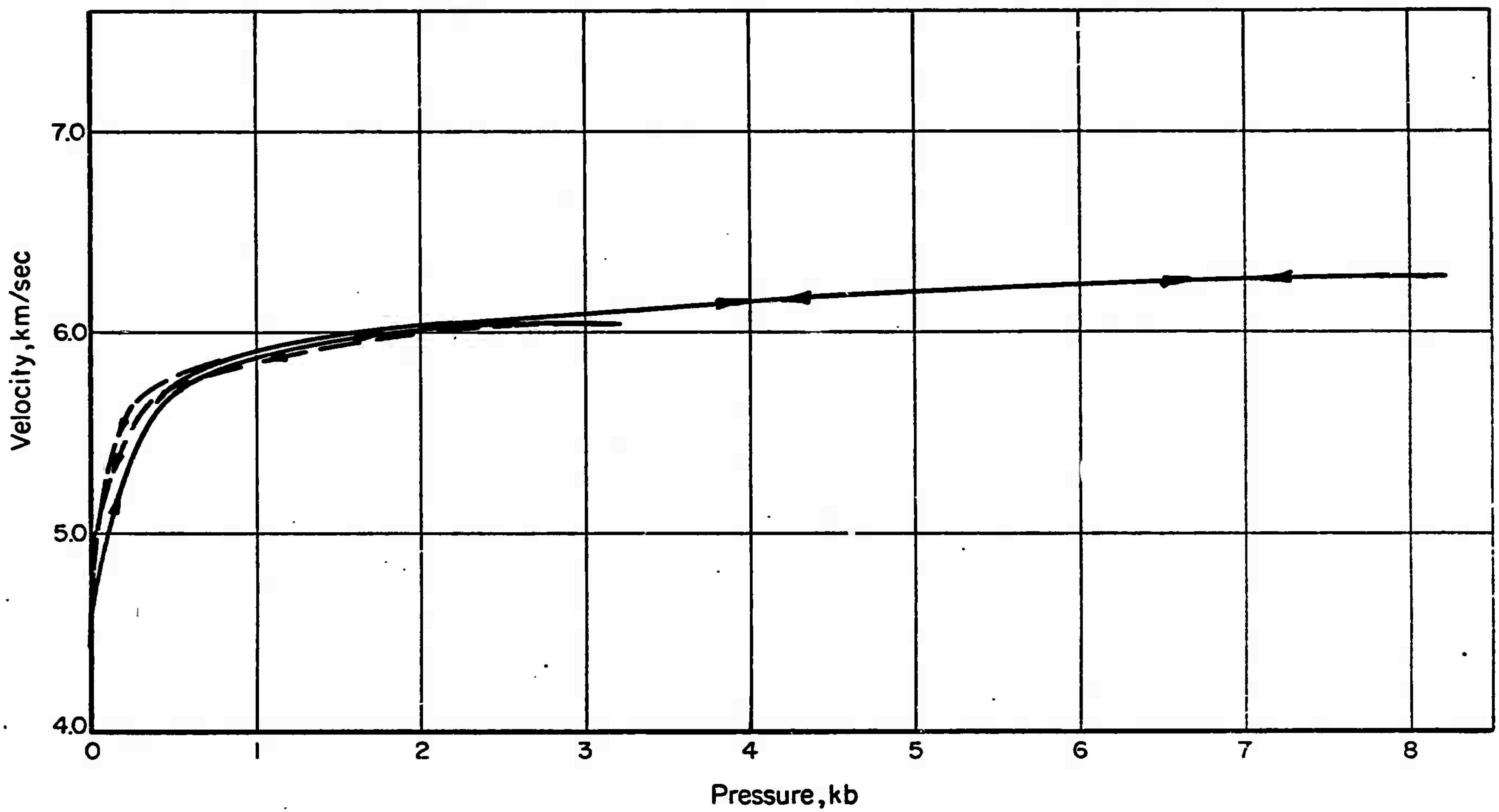


FIGURE 21. COMPRESSIONAL VELOCITY DRY WESTERLY GRANITE

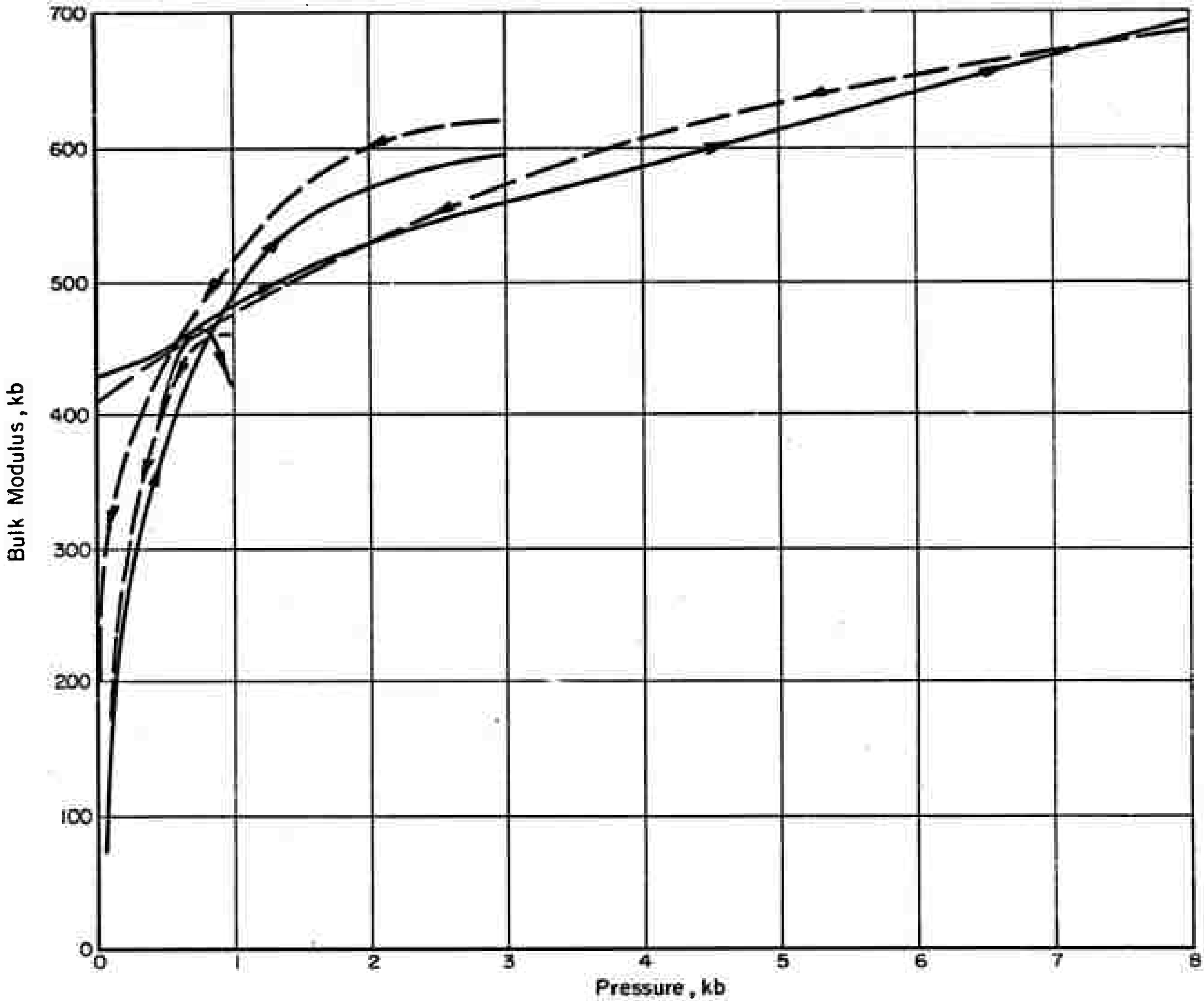


FIGURE 22. BULK MODULUS DRY WESTERLY GRANITE FROM VOLUME MEASUREMENTS

Salem Limestone. The Salem limestone showed the anticipated decreased compressibility and crush up, Appendix I and II, EXP 1025-21. The Bureau of Mines has reported a porosity of 12.5 percent and a permeability of 0.7 millidarcy for this material.[13] Our measurements on water content indicate filling 10.9 percent of pore space. Because of the low permeability of the limestone, it is quite likely that the water did not fill all the pore space measured in a helium porosity test. If so, it cannot be established unambiguously that the crush up is due to the difference in compressibility between the water and the limestone or due to the closure of unfilled pores. The velocity curve, Figure 23, is of no help because the obviously reduced values would be the result of cracks formed on the closure of unfilled pores.

The shear velocity experiments on the limestone were attempted before the new specimen design was perfected. As these results are not completely reliable the acoustic values of the elastic moduli have not been determined.

Figure 24 plots the bulk modulus of the water-filled Salem limestone. Curves A, C, and E are compression; Curves B, D, and F, the corresponding pressure release. The rise in bulk modulus in the low pressure region of curve F is not explained.

Berea Sandstone. The Berea sandstone has a larger porosity, 19.1 percent, and a much greater permeability, 50 millidarcies, than the limestone.[13] Therefore, this rock should act as an open system to the fluid in contrast to the "closed" limestone. We were able to fill only 16.9 percent of the specimen with water. This is consistent with our measured dry density value which is 2.2 percent greater than that reported by the Bureau of Mines[13].

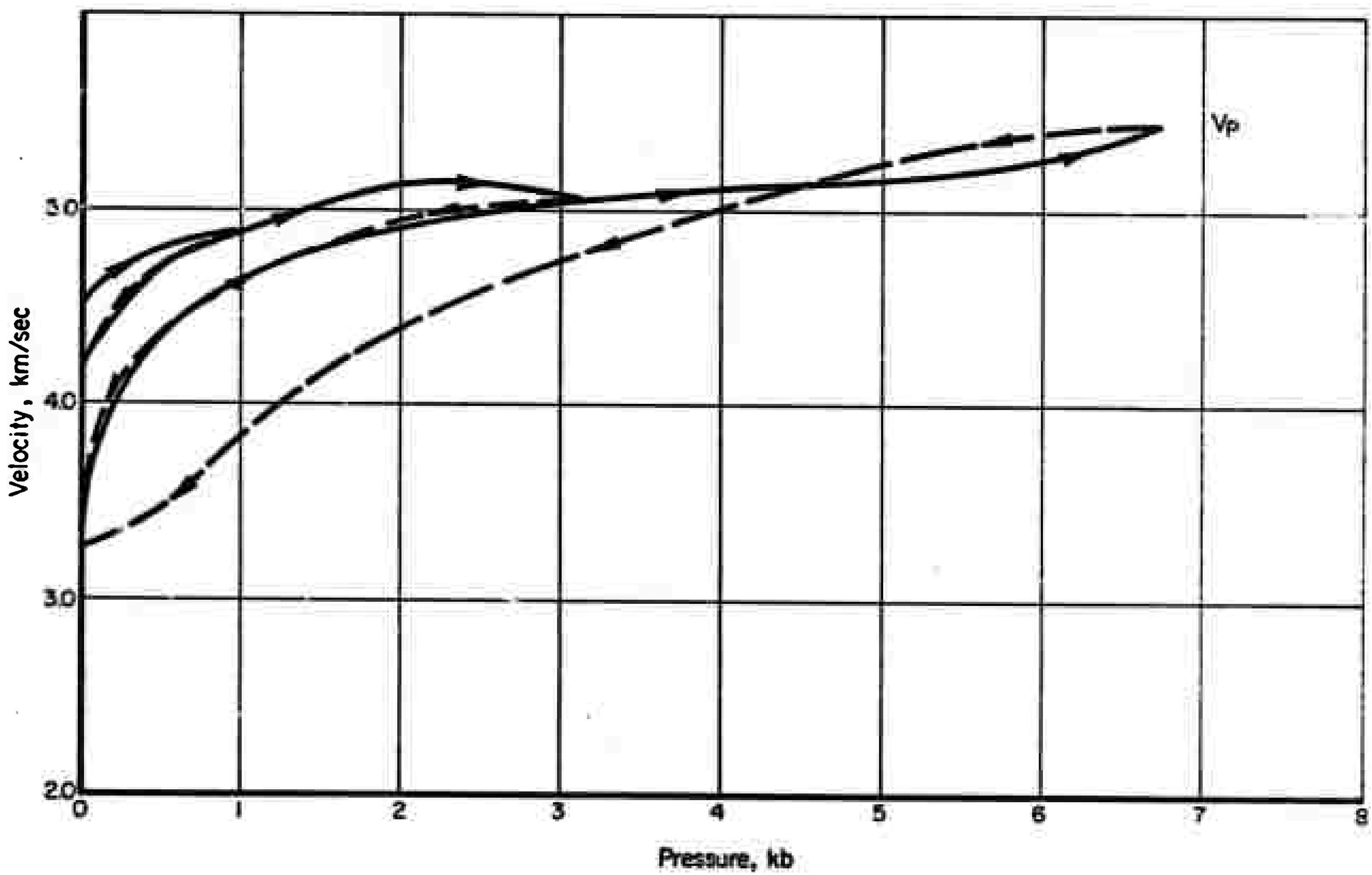


FIGURE 23. COMPRESSIONAL VELOCITY WATER-FILLED SALEM LIMESTONE

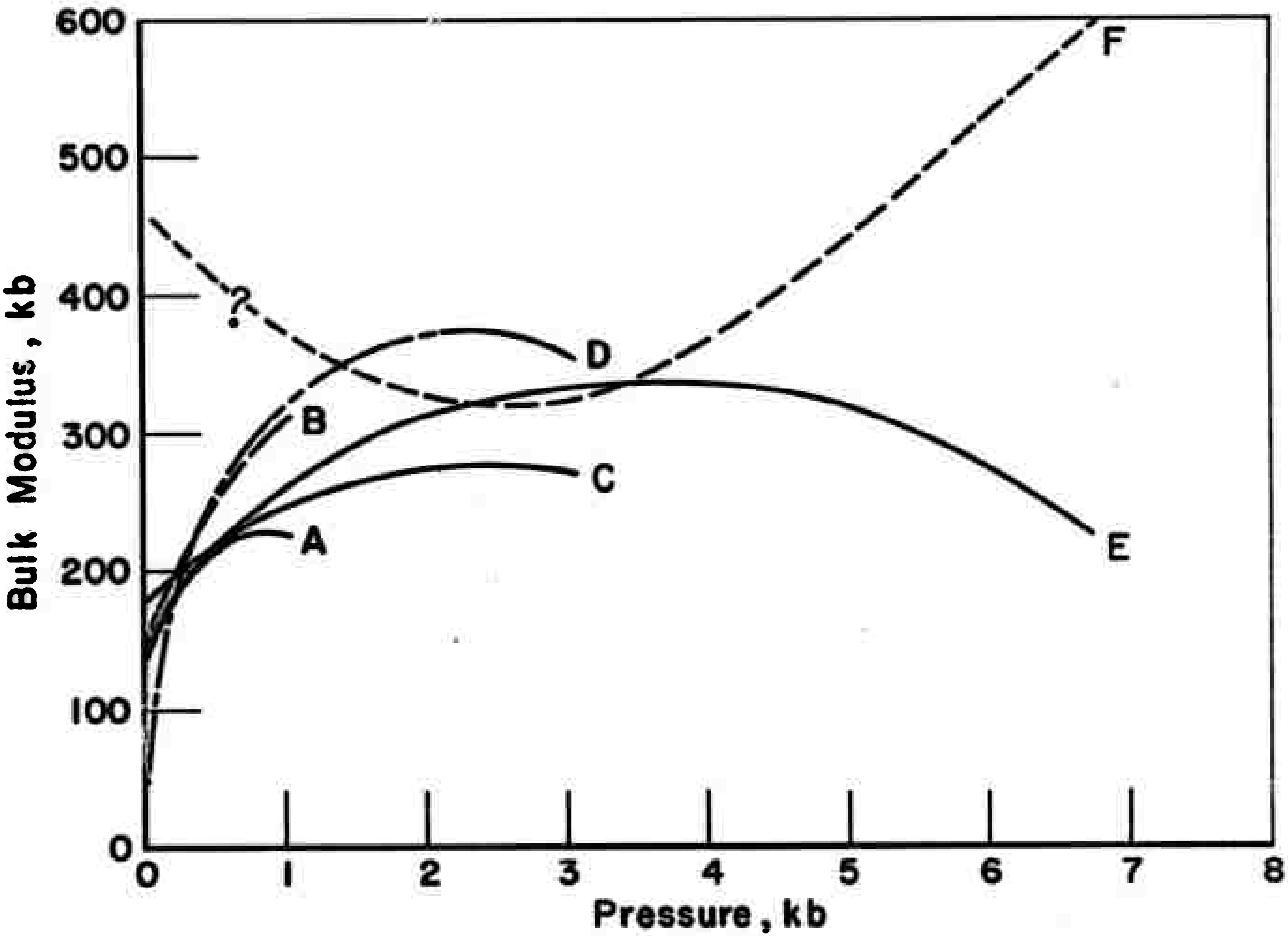


FIGURE 24. BULK MODULUS WATER-FILLED SALEM LIMESTONE FROM VOLUME MEASUREMENTS CYCLED 0-1-0-3-0-7-0 KB

It is difficult to observe from the volume data, Appendix II, EXP 1025-22, whether or not a crush up occurs in this material. However, the volume bulk modulus and velocity bulk modulus seem to clearly indicate this, Figure 25 and Figure 26.

These results indicate that the largest effects of the fluid result from reducing the crushing mode of failure to a minimum. On pressure increase, the volume bulk modulus shows only slight decrease as compared to the dry rock which has a pronounced minimum, Figure 19. As expected, from results of Nur and Simmons[14], the water filling increased the compressional wave velocity and did not affect the shear wave velocity. The velocity decrease on pressure release of the dry samples was obviously less pronounced in the fluid filled sample, Figure 27.

Figure 27 shows four excursions to 7 kb for the compressional velocity. After the first three excursions to 7 kb, velocity drops off. However, on the 4th cycle the up and down cycles almost coincide. It appears as if an equilibrium condition is being reached. The volume modulus data show this also (not plotted), but they are not nearly as sensitive an indicator as the velocity data.

<u>Westerly Granite</u>. Shear velocity measurements have not yet been made. The compressional wave velocity data, Figure 28, are interesting in that they suggest that cyclic loading is increasing the crack density rapidly and steadily. If so, this may be important to rapid excavation in hard rock for an increased crack density may mean easier material breakage.

In Figure 28 the low pressure data starts out as shown by Nur and Simmons[14]. In fact, the locus of points of the maximum of the three curves versus pressure would fall close to their reported curve. What is interesting is that on pressure release from each of these 3 cycles, we have large drop

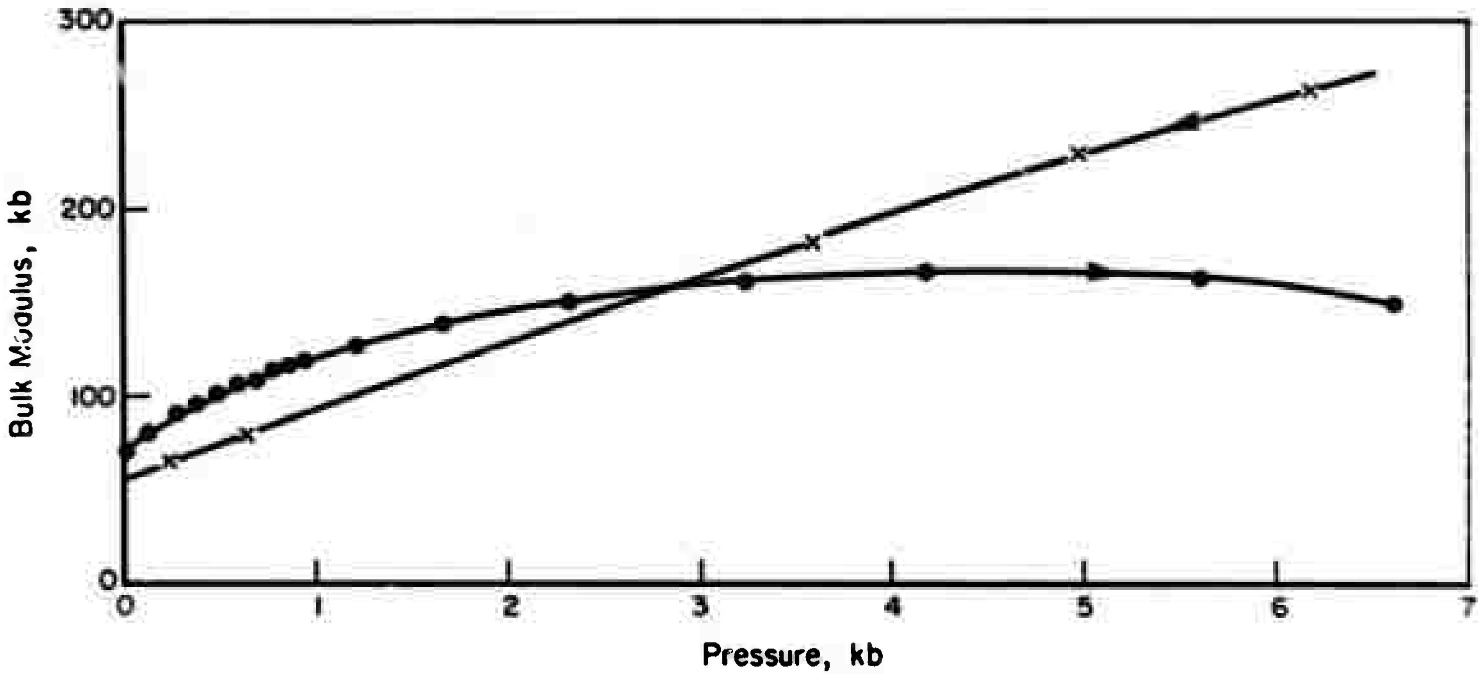


FIGURE 25. BULK MODULUS FROM VOLUME MEASUREMENTS OF WATER-FILLED BEREA SANDSTONE 0-6.6-0 KB CYCLE

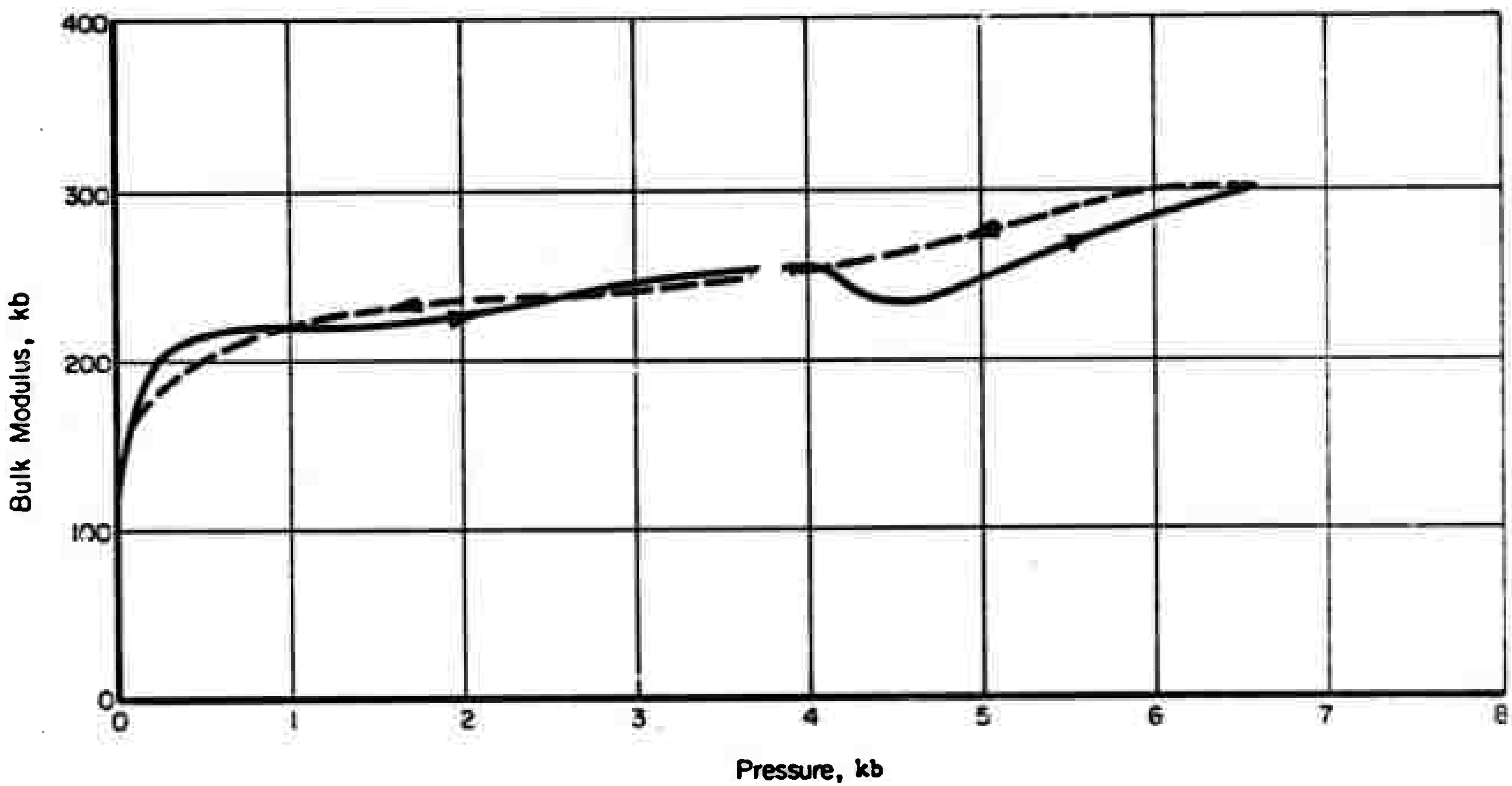


FIGURE 26. BULK MODULUS OF BEREA SANDSTONE FROM ACOUSTIC VELOCITY MEASUREMENTS, CYCLED 0-6.6-0 KB

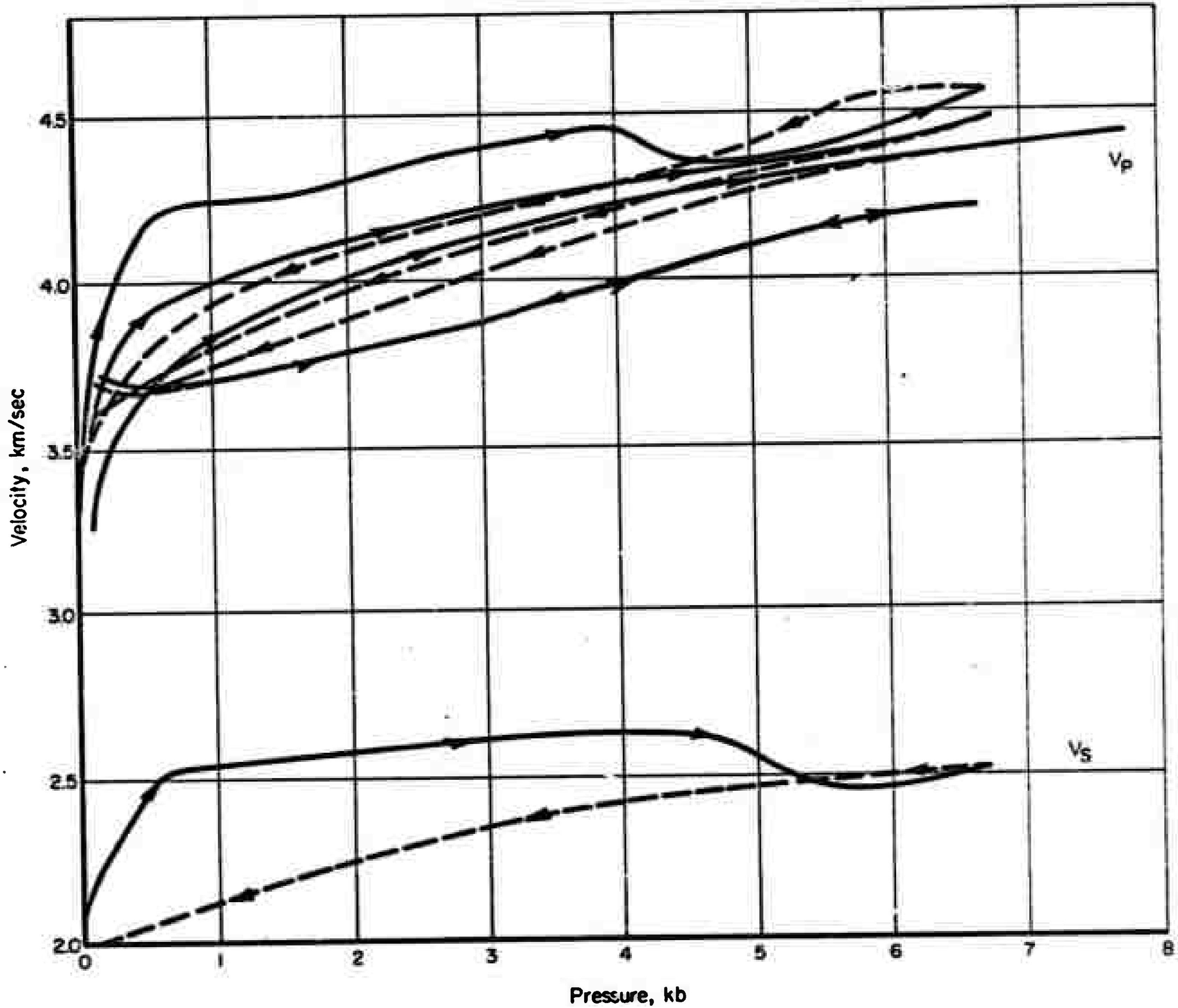


FIGURE 27. ACOUSTIC VELOCITY OF WATER-FILLED BEREA SANDSTONE

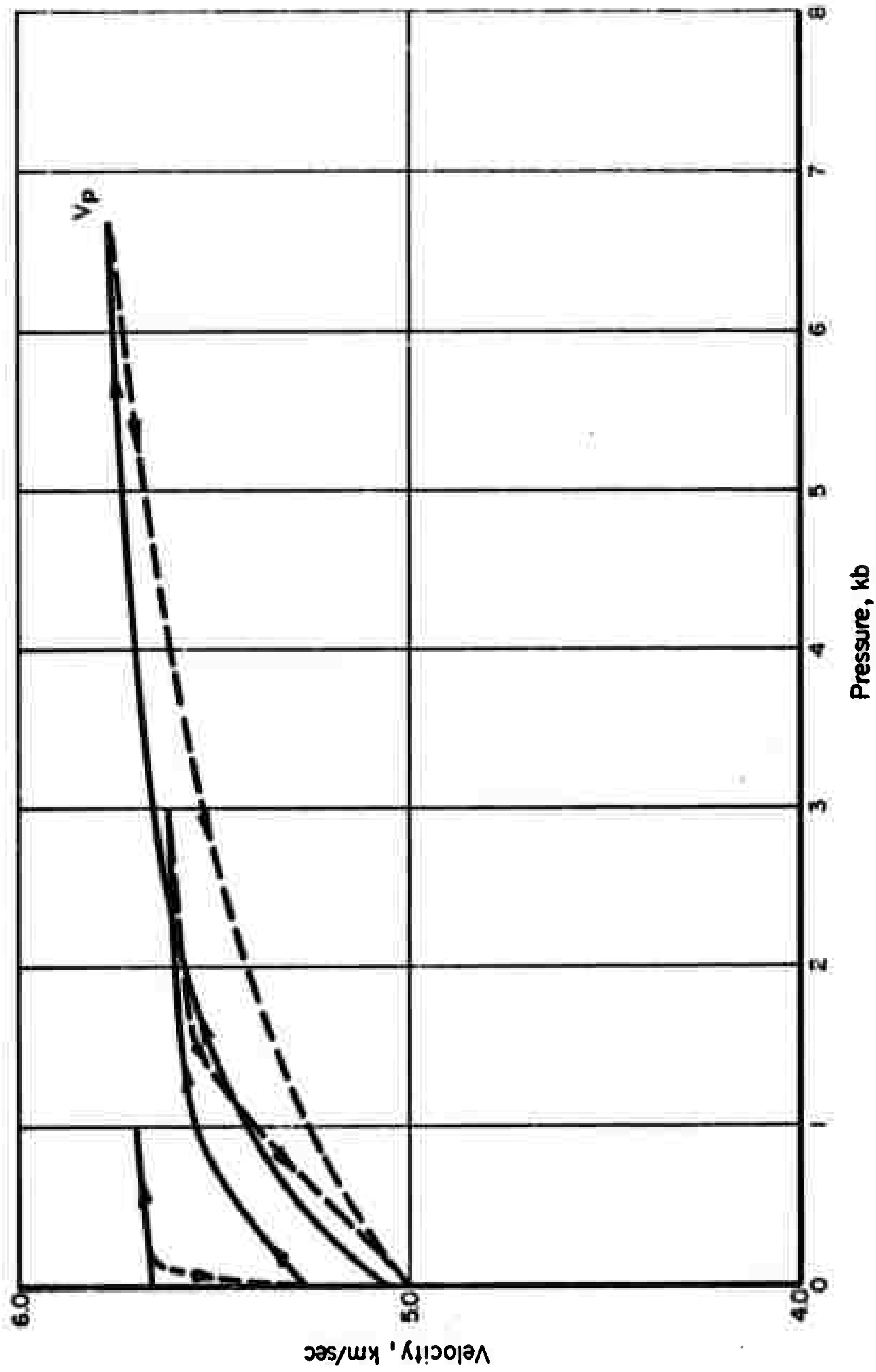


FIGURE 28. COMPRESSIONAL VELOCITY OF WATER-FILLED WESTERLY GRANITE

offs in velocity. All indications from the present work as well as that of other workers indicate that this drop off is caused by an increase in thin cracks. The volume data in Appendix I, EXP 1025-24, seem to confirm this by showing a positive volume increase on return to zero pressure from the 1-kb and 3-kb cycles. This may indicate an improved method of rock fracture or suggest more rapid excavation would occur in saturated hard rocks than in dry hard rocks.

DISCUSSION

Dry Rocks

Hydrostatic pressure loading of most dry rocks produces a similar sequence of effects on their elastic moduli. The magnitude and pressure range of these effects is dependent on the porosity, microcracks, grain size, previous pressure cycling and orientation, as well as the intrinsic elastic properties of the rock material. At low confining pressures the elastic moduli of rocks change and increase rapidly. This effect is generally limited to the first few hundred bars and is caused by the closing of fine cracks. At higher pressures changes occur much more slowly. At still higher pressures, pores (the approximately equidimensional voids) close; this pore closure can have a profound effect on the elastic moduli of the rock.

These experiments have shown that the phenomena described above have significantly different effects on the elastic moduli as determined by static and dynamic methods. The most significant results observed are the effects associated with the crushing mode of failure. The pore closure causes a significant decrease in the values determined by volume techniques, but not in the acoustic values. However, the acoustic values seem to show

a characteristic depression or knee in the velocity-pressure curve.

Another important result observed is the difference in release phenomena. Hard, brittle, porous rock, e.g., sandstone, shows immediate decrease in velocity on pressure release after crush up. This is negative hysteresis. Ductile materials, e.g., limestone, show a positive velocity hysteresis immediately on pressure release. However, for both rocks the volume bulk modulus on pressure release is significantly greater than the velocity modulus.

Figure 29 is a plot of the bulk modulus of dry Salem limestone with small pressure releases (1) and rises (2). This was accomplished by dropping the pressure ~ 100 bars at the plotted pressure and then raising it ~ 100 bars. Thus, values of bulk modulus were obtained at small pressure decreases and pressure rises at high pressure in addition to the values obtained by pressurizing in a continuous direction, Curve C. The values obtained this way for pressure release and rise generally bracket the corresponding velocity value. In addition the immediate pressure-release values of bulk modulus for the other data found in this report are always greater than the acoustically determined values. This difference between the acoustic and static values cannot be attributed strictly to the fact that the acoustic wave is more sensitive to the microcracks than the static values. These results suggest that the acoustic pulse--which is a slight alternating pressure pulse superimposed on the average stress--in effect measures an average compression and release value of the modulus. This statement is only true when the crush up is not occurring. It is, however, true at any cycle point in the middle of the crushing mode of failure range.

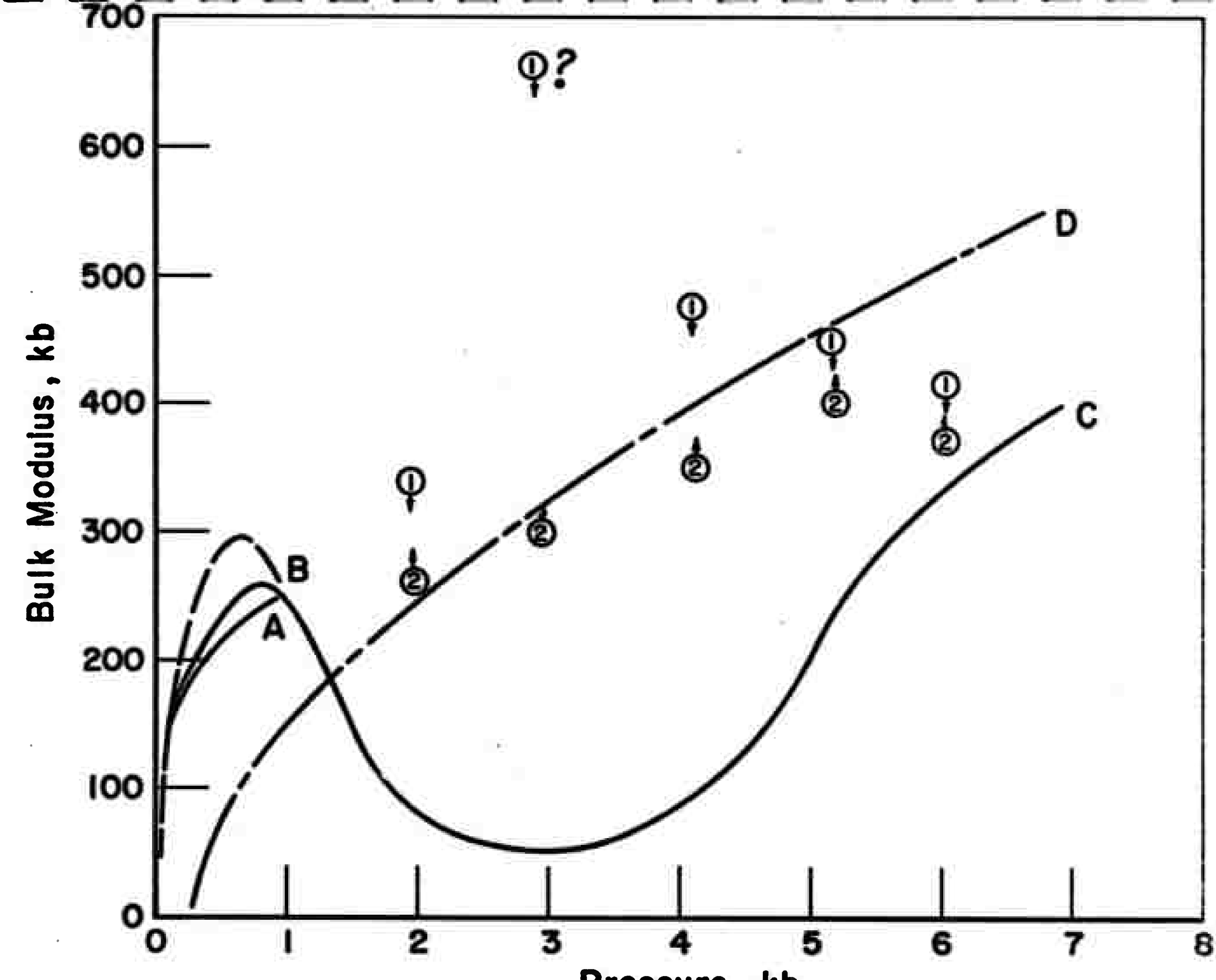


FIGURE 29. BULK MODULUS DRY SALEM LIMESTONE FROM VOLUME MEASUREMENTS CYCLED WITH SLIGHT PRESSURE DROPS

Water-Filled Samples

Hydrostatic pressure loading of water-filled rocks produces significantly different results than those found in the same rocks dry. The obvious effect of a large decrease in compressibility is observed.

The velocity results on the first cycle are in general agreement with Nur and Simmons[14] who found an increase in compressional wave velocity and little change in shear wave velocity with water filling.

The much larger compressibility of water than the rock produces results that are significantly different in our closed system than in an open system. In the open system one measures the compressibility of the rock network. In the closed system one measures the compressibility of the rock and liquid.

The rock network has strength so that the observed compressibility lies between that of an open system and closed system of unconnected grains. The difference in compressibility between the rock and water will result in the pore pressure being less than the confining pressure. This difference in pore and confining pressure will result in an effective empty volume for the porous rocks, e.g., the limestone and the sandstone to crush into. Our results show this.

The crush up can continue until the pore and confining pressure become equal. The water-filled limestone exhibits this crush up at pressures greater than 5 kb; the water-filled sandstone shows this near 7 kb.

The results on the granite are not conclusive but they suggest that cycling water-filled specimens results in cracking. If this is so, it may also suggest that repeated low pressure loadings may be as effective as a single high pressure loading in fracturing this rock.

Comparison with Other Work

Peselnick[15] and Peselnick and Wilson[16] have shown for Solenhofen limestone of density 2.53 to 2.66 g/cc that the 1-atmosphere velocity is a linear function of density. They have also shown that these values extrapolate well into the Voigt-Reuss averages (of single crystal calcite V_p and V_s) for a polycrystalline aggregate of theoretical density 2.712 g/cc, Figure 30. Also plotted on Figure 30 are the values of velocity versus density found in the present work.

Except for the low-pressure region where microcracks affect the velocity, the results of the present work fit well the curve found by Peselnick. Also plotted on the figure are the velocity data of Schock, Louis, and Lilly[12] versus the volume density measurements of Duba and Schock[17] for Solenhofen limestone samples taken from the same large specimen. Again these results agree with the velocity-density curves of Peselnick[15] except for the low-pressure region where microcracks are expected to affect the velocity.

These results suggest three different regimes where the velocity is a linear function of density: $V = a + b\rho$. For the pressure regime where microcracks control the velocity, the values of a and b are not well defined but b ranges from 44 to 170. The value for b is quite close to 44 on the release from 5 kb and 7 kb and the intervening recompression as well as for the data of Schock, et al.[12] It is 170 on initial compression. At present there is insufficient data to resolve the value of b. The important point is that velocity is a very steep function of density in the region of microcracks. If one decides on an initial value for the coefficient b, the coefficient a can be determined from initial density and initial velocity. The same observation can be made for V_s where the value for b = 27 for the 5 kb and 7 kb regions of the cycles.

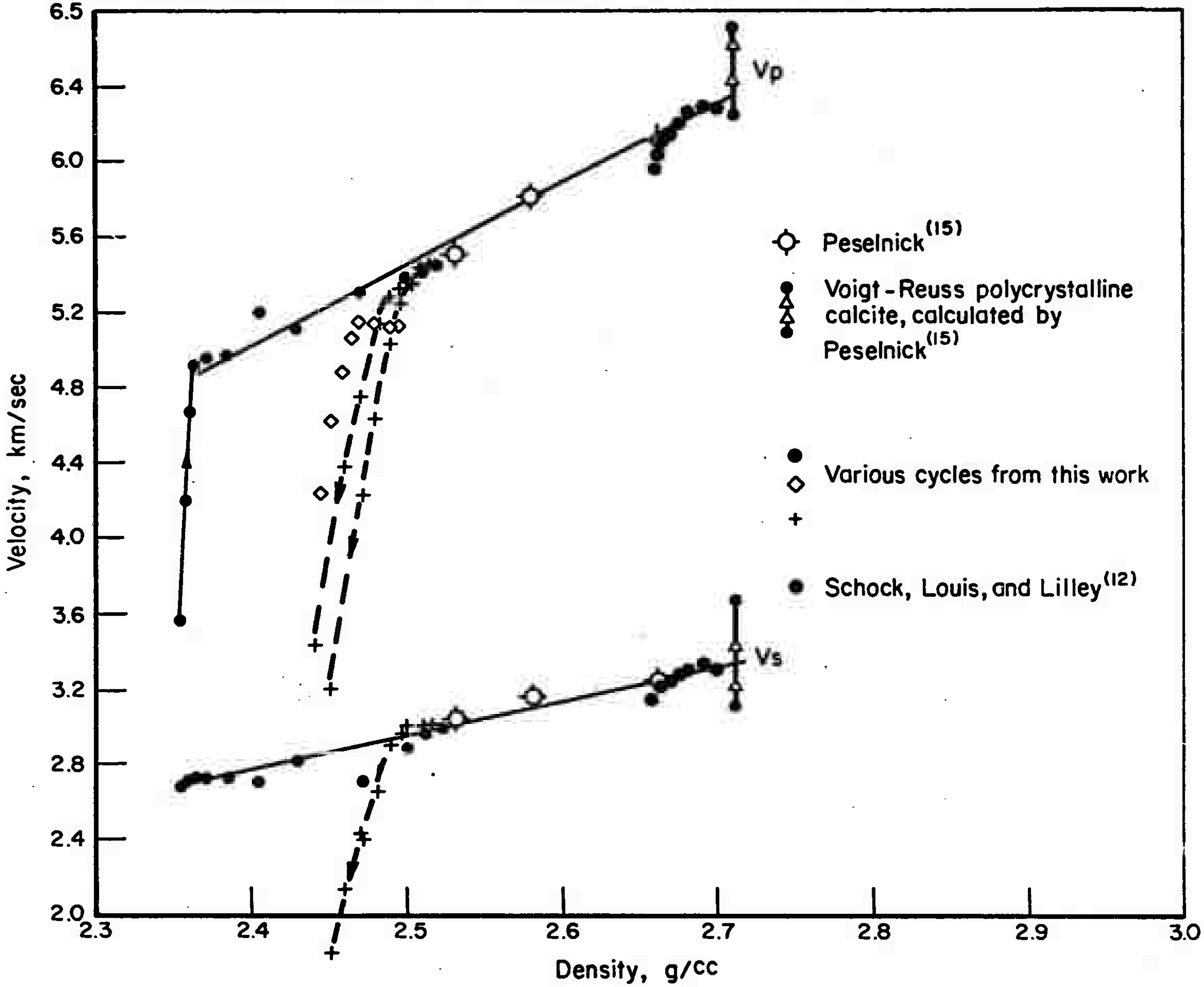


FIGURE 30. VELOCITY-DENSITY PLOTS FOR VARIOUS LIMESTONES

Because of the large value of the b coefficient these microcrack-region curves meet the second curve, i.e., the velocity curves in the region where porosity closure is influencing the density. These latter curves were first noted by Peselnick[15] who obtained the following relationships

$$V_p = -7.41 + 5.11\,\rho \quad ,$$

and

$$V_s = -1.086 + 1.625\,\rho \; .$$

Present experiments obtain the following relationships

$$V_p = -5.65 + 4.45\,\rho$$

$$V_s = -1.61 + 1.83\,\rho \quad ,$$

which give values of velocity quite close to those computed by Peselnick. The third region is not shown on Figure 30 but is the region where V_p and V_s would correspond to a completely dense material.

This interpretation differs from that of Peselnick. He plotted the high pressure V_p data on Solenhofen limestone of Hughes and Cross[18] on his V_p versus ρ plot. He found that the curve had a slope of 3.04 versus the 1-atmosphere slope of 5.11. He used the difference in the two slopes to deduce the effect of porosity on the velocity of an aggregate of calcite.

Hughes and Cross[18] did not determine the density of their sample at pressure. To plot Hughes and Cross' data Peselnick[15] had to calculate the density; he did this by using Bridgman's[19] data on calcite single crystal: $K = 1.32\ (10^{-6})$ per bar. Solenhofen limestone is a porous material and has a compressibility significantly larger than that of a single crystal of calcite. The sample of Duba and Schock[17] is quite similar to that of Hughes and Cross. Duba and Schock have determined a value of $1.94\ (10^{-6})$ per bar for the compressibility at one atmosphere. Using the data of Duba and Schock, Hughes and Cross' velocity values fall very close to Peselnick's curve with the 5.11 slope.

The present interpretation is believed to be more correct. As a result, the effect of porosity on velocity in a polycrystalline aggregate of calcite can be evaluated only when the V-versus-density data for a nonporous sample is available. Results do suggest, however, that if one knows the 1-atmosphere velocity, a static determination of density versus pressure will permit a good estimation of velocity at high pressure. Additional work needs to be done to refine and confirm this observation. It is significant to note that this observation appears valid even during crush up. An exception to this would be the knee in the velocity curve associated with the initiation of crush up.

Peselnick[15] showed a similar but different relationship between velocity and density for water-saturated Solenhofen limestone. The present data on the Salem limestone neither confirm or deny his results. As noted earlier, the Salem limestone has a low permeability and the technique probably did not saturate the sample. Thus, the velocity-versus-density values are influenced by microcrack closure as noted before. This is indicated also on Figure 30.

The Salem limestone is ductile above 1.5 kb[9] while the Berea sandstone is brittle at all pressures used. As noted, many similarities exist between the behaviors of these materials, e.g., effects of microcracks on velocity, crush up, the knee in the velocity curve associated with crush up, permanent volume decrease after crush up, and a general similarity in comparison of static and dynamic elastic constants. A significant difference seen in the release curves is attributed to the differences in ductility between the two materials.

Figure 31 is a plot of velocity versus density for the present results. The effects of microcracks, knee in the velocity curve, crush up,

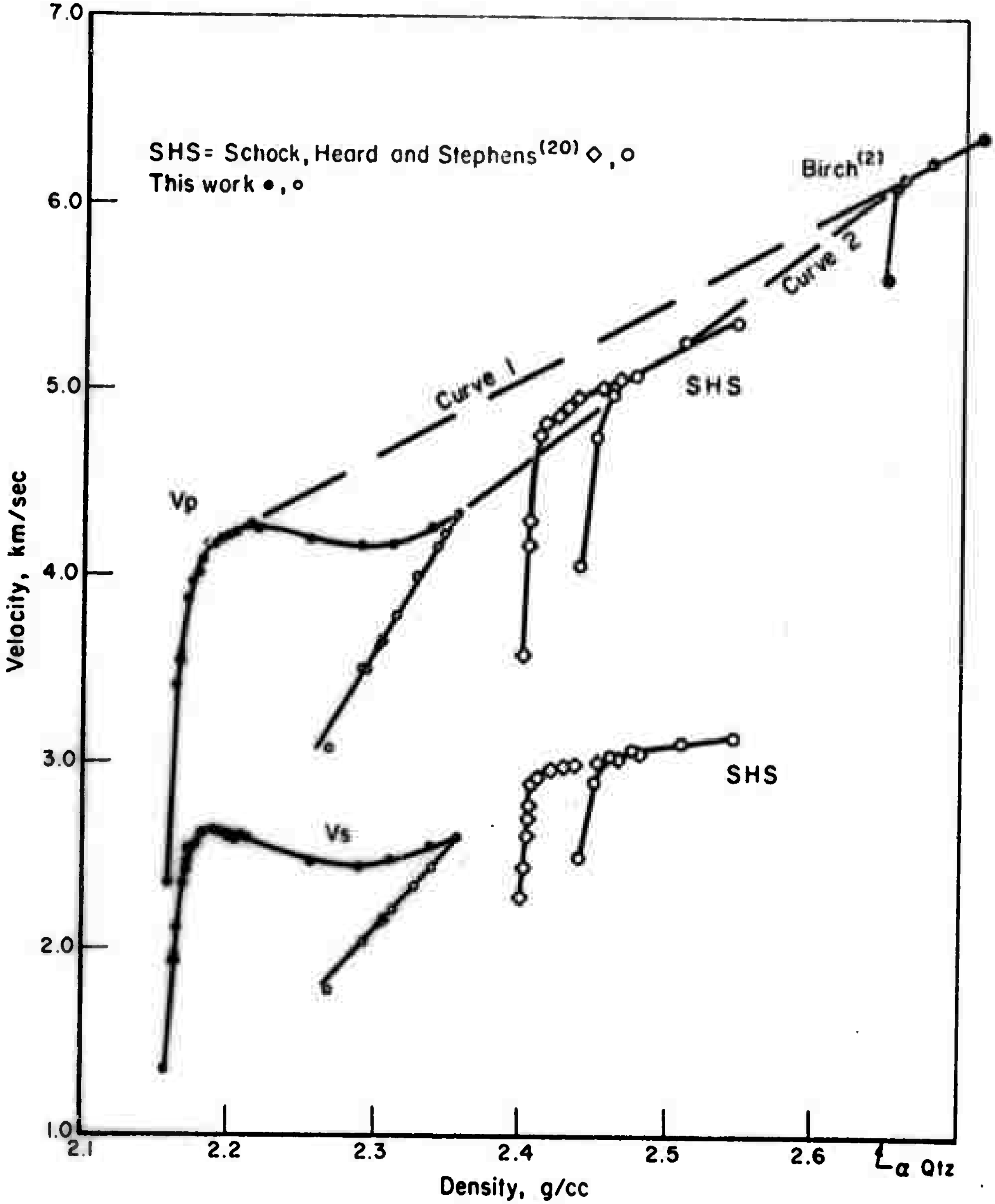


FIGURE 31. VELOCITY-DENSITY PLOTS FOR SANDSTONE

and pressure release are clearly evident. Also plotted in this figure are data for the Wagonwheel sandstone of Schock, Heard, and Stephens[20] and data from Birch[2] on a quartzite. This figure suggests that for different porous rocks made up of the brittle material quartz there is a relationship of velocity to density similar to that found in limestone. Two curves are drawn for the V_p relationship. Curve 2 was drawn as an extension of the data of the present work through the high-pressure points of Birch. The data of Schock, Heard, and Stephens[20] fall very close to it at pressures above the microcrack region.

Curve 1 was drawn from the maximum V_p of the present work through Birch's maximum. The reason for this is that this maximum represents the highest velocity that the sample can achieve before crushing and the subsequent drop in velocity occurs. It was anticipated that sands of higher density would attain velocities found on this curve before the effects of crushing occurred. The data of Schock, Heard, and Stephens seem to suggest that this does not happen.

It is noted that the slopes of the curves of Schock, et al., and Birch are noticeably less than that for Curve 2, Figure 31. Birch's curve can be attributed to that of an essentially theoretically dense sample for his ρ_o = 2.647 versus ρ_o = 2.648 for quartz. The data of Schock are not so constrained and another explanation must be found. This type of behavior would be associated with the initial part of the decrease in velocity associated with crush up. The data of Schock, et al., are not conclusive, but there appears to be a region of increased compressibility in the 13 - 15-kb region that would indicate a slight crush up occurring just above the 10-kb maximum pressure of the velocity data.

This is clearly speculative, however. It should be pointed out that the curve made up of the diamond symbols in Figure 31 is actually more

favorably plotted than is really the case. In calculating the density for each velocity Schock, et al[20], used an integration technique of the bulk modulus determined from the velocity. This is valid only for completely dense materials; the values they plotted are low, probably by about 0.05 gm/cc at 10 kb. The density of the curves associated with the circles do not have this defect.

Phenomenological Explanation

Scholz[21] has shown that Griffith's criteria of brittle fracture is not applicable to rock because inhomogeneities in the rock produce fluctuations in the stress field sufficient to arrest the cracks shortly after they are initiated. Proceeding from this approach he has introduced a statistical model of applied stress to local stress which predicts microfracturing, i.e., small-scale failure in the rock. Essentially his model introduces stress (σ) at any point in the rock body as a probability function of the applied stress ($\bar{\sigma}$). Thus, there will be local stress (σ) higher and lower than $\bar{\sigma}$. When the local stress exceeds the strength, local fracture will occur. This will be random throughout the rock body. As $\bar{\sigma}$ increases, more and more microfracturing will occur.

Scholz's results can be used to explain the observations of the present program. After the initial microcracks are closed by pressure, rock is stressed quite like that suggested by Scholz.[21] The increase in pressure brings an increase in velocity due to increased transmission caused by squeezing the grains together. As the pressure increases small local regions microfracture; these are new regions of low acoustic transmission until additional pressure application closes the new microcracks. However, at lower pressures the increase in velocity is much greater than the decrease caused by the limited amount of microfracturing.

As the pressure is increased in porous rocks, more and more grains will be stressed above their strength. If the distribution function is sharp enough many grains will fail over a relatively small pressure interval and the attendant microfracturing will cause a decrease in velocity as observed in the present experiments. After this occurs the rock can still have some porosity because it has a shear strength or the reduction in size has spread out the load, i.e., there is a new distribution function. Then, it is conceivable that additional crushing episodes may occur.

From this analysis we see that for brittle materials with porosity, static and dynamic measurements of the elastic moduli are not strictly comparable because they are not measuring the same thing. The velocities used to determine the dynamic elastic constants are not only a function of the intrinsic properties of the material but also of porosity, amount of microcracks, past pressure cycling, water content, and pressure regime. The static values are representative of the rock as a whole. Thus, we can have the situation, as in the Berea sandstone, where the acoustic bulk modulus shows a negative hysteresis on pressure release while the static values show a positive hysteresis. On the basis of these results it can be predicted that triaxial tests used to define other moduli would not agree with the dynamic values.

There are not enough results to date to compare these results with those on Westerly granite (or other "hard rocks"). The data that are available here and in the literature suggest that it may behave in a manner similar to the Berea sandstone but over a smaller velocity and density range.

CONCLUSIONS AND RECOMMENDATIONS

The work of this research program has shown that hydrostatic pressure loading of rocks can produce significantly different values in their elastic moduli when measured by two different techniques, static and dynamic. These differences are ascribed to the effects of thin cracks and the more equidimensional pores. The most significant results observed are the effects associated with the crush up of the pores. This causes a significant decrease in the volume bulk modulus but not the bulk modulus determined from acoustic velocity.

Interestingly, there appears to be an indication of this crush up in the velocity curves. This is indicated by a slight knee (as in the case of Salem limestone) or a slight decrease (as in the case of the Berea sandstone) in the velocity near the initiation of the crush up. Similar crush-up effects were observed in wet and dry samples; the effects in the dry samples were much more pronounced.

The brittleness of the rock minerals plays an important role in the different bulk moduli values observed on pressure release. This effect is very pronounced in rock composed of a brittle material like quartz, e.g, the Berea sandstone. The dynamic bulk modulus decreases instantly on pressure release. In the more ductile limestone this does not become less than that on pressure rise until very low pressure.

The volume bulk modulus is always greater than the acoustically determined value immediately after pressure release. In general it is significantly less on compression. This bracketing of the acoustically determined modulus by the volume compression and release values suggests that the acoustic pulse--which is a slight alternating pressure pulse superimposed on the average stress--in effect measures the average value of the modulus.

We have attempted to explain these results by Scholz's[21] statistical model of applied stress to local stress which predicts microfracturing. Applied stress which causes the local stress to be less than the fracture strength produces increased velocity as well as increased static and dynamic elastic moduli. When the local stress exceeds the fracture stress, failure occurs creating new cracks which impede the acoustic transmission. The crushing mode of failure is observed when the local stress exceeds the fracture stress in a large number of grains. This produces a significant decrease in the volume bulk modulus but only a minor depression in the acoustic values. The ductile-brittle properties of the minerals have a large effect in determining the stress distribution on pressure release. This has been shown to influence the bulk moduli determined by the two techniques.

The present results have been used to confirm and extend the suggestion of Peselnick that there is a linear density versus velocity relationship for porous limestone. We have shown that this relationship is valid for the pressure region above the closure of microcracks. Thus it should be possible to estimate the acoustically determined elastic moduli from volume compressibility.

A similar relationship has been developed for sandstone. These results are complicated by crush up in low density sandstone and need further study.

The program objective was to utilize simultaneous acoustic and volume measurements to understand differences and similarities between the dynamic and static elastic moduli of rocks. Other program objectives were to examine the effects of cyclic loading and water filling. Work to date has determined the bulk modulus by volume techniques and the dynamic moduli by acoustic techniques for Salem limestone, Berea sandstone, and Westerly granite.

Significant moduli differences have been observed in the two techniques. These results can be very useful to the sponsor's program. Because of the sensitivity of the acoustic velocity to microcracking it is suggested that microseismic techniques will be a valuable method to examine ground support problems as well as crack density ahead of a mining machine. (The crack density could be used as a means to evaluate fracturing ability.) Conversely, the sensitivity of acoustic methods to cracks suggests that they may be poor in evaluating the bulk response of rock to loading. Thus the sponsor may find that elastic moduli determined by volume techniques are required for predictive computer codes. The cyclic loading experiments show continuing changes in the bulk moduli which will have to be accounted for in these predictive techniques.

Initial measurements on a water-filled Westerly granite suggest that cyclic loading increases the crack density. If an increase in crack density signifies easier rock removal--as it must in the extreme--then this result suggests an approach which may result in more rapid and easier excavation in water-filled hard rocks. The rock would be hit with an initial low pressure loading to initiate cracks followed by a higher pressure loading to remove material. Since the higher pressure loading would be less than that required to remove the rock in a single blow considerable costs savings in equipment repair and down time can be envisioned.

We would recommend further work on this program to examine these results in more detail. Because of the broad-based exploratory nature of the program duplicate runs were often not made. The experimental findings would benefit from duplication. The samples should be examined by our refined velocity technique (Figure 5) which permits simultaneous compression and shear wave measurements in order to relate the results in greater detail. Studies in a triaxial test device to measure all the static moduli would be of value

in understanding the similarities and differences between the acoustic and volume determinations of elastic moduli. These additional results would certainly find valuable application to the problem of rapid excavation in hard rocks.

REFERENCES

(1) E. Williamson and L. H. Adams, J. of the Franklin Institute, 195, pp 475-529 (1923).

(2) F. R. Birch, J. Geophys. Res., 66, pp 1083-1102 (1960).

(3) J. M. Ide, Proc. Mat. Acad. Sci., 22, pp 81-91 (1936).

(4) G. Simmons and W. Brace, J. Geophys. Res., 70, pp 5649-5656 (1965).

(5) P. N. La Mori, Ph.D. Thesis, 205 pages, Northwestern University, Evanston, Illinois (1967).

(6) P. N. La Mori, DASA Report 2527, 78 pages (1970).

(7) D. Stephens, UCLRL Report.

(8) R. Schock, personal communication.

(9) H. Heard, Geol. Soc. Amer., Memoir 79, p 193, 382 pages (1960).

(10) I. Borg, M. Friedman, J. Handin, and D. V. Higgs, Geol. Soc. Memoir 79, p. 133, 382 pages (1966).

(11) W. F. Brace, A. S. Orange, and T. R. Madden, J. Geophys. Res., 70, p. 5669 (1965).

(12) R. Schock, H. Louis, E. M. Lilly, UCRL-50750, University of California, LRL, 38 pages (1969).

(13) U. S. Bureau of Mines, Frank Henderson, Personal Communication.

(14) A. Nur and G. Simmons, Earth and Planetary Sci. Let., 7, pp 183-193 (1969).

(15) Louis Peselnick, J. Geophy. Res., 67, pp 4441-4448 (1962).

(16) Louis Peselnick and William H. Wilson, J. Geophy. Res., 73, pp 3271-3280 (1968).

(17) A. G. Duba and R. N. Schock, UCRL-50852, University of California, LRL, 18 pages (1970).

(18) D. S. Hughes and J. H. Cross, Geophysics, 16, pp 577-593 (1951).

(19) P. W. Bridgman, Am. J. Sci., 1, pp 81-102 (1924).

(20) R. N. Schock, H. C. Heard, and D. R. Stephens, Project Wagon Wheel, Technical Studies Report, pp 65-77, El Paso Natural Gas Company, El Paso, Texas, 248 pages (1971).

(21) C. H. Scholz, J. Geophy. Res., 73, pp 1417-1432 (1968).

APPENDIX I

```
      PROGRAM EOS2(INPUT,OUTPUT,PUNCH)
CC  THIS PROGRAM REDUCES THE RAW DATA FOR SIMULTANEOUS MEASUREMENT OF
CC  DELAY AND LINEAR STRAIN TO VELOCITY, AXIAL LINEAR STRAIN, RADIAL
CC  LINEAR STRAIN VERSUS PRESSURE. VELOCITY IS EXPRESSED AS KM/SEC OR
CC  AS MM/MICROSEC. STRAIN AS -DL/L. THE PROGRAM ALSO COMPUTES VOLUME
CC  STRAIN (-DV/V) =  -DL/L(AXIAL)+2(-DL/L(RADIAL)).CORRECTION FACTORS
CC  ARE ACCOUNTED FOR. THE DELAY IN THE SYSTEM (0.55 MICROSEC) FOR
CC  VELOCITY, THE STRAIN IS MEASURED AGAINST AN IRON STANDARD WITH A
CC  COPPER JACKET. PRESSURE IS MEASURED WITH A MANGANIN CELL CALIBRATED
CC  WITH A HEISE GAGE TO 3 KB DURING EACH EXPERIMENT. THIS CALIBRATION
CC  IS ESSENTIALLY CONSTANT. THE PROGRAM TAKES INTO ACCOUNT MISSING OR
CC  NONEXISTANT DATA POINTS OF VELOCITY OR STRAIN BY SETTING THEIR VALUE
CC  TO -0.0. PLOTS OF VELOCITY AND STRAIN VERSUS PRESSURE ARE PRODUCED
CC  WITH THE CALL QIKPLT. THE PROGRAM DETERMINES THE BEST COORDINATE
CC  SCALE FOR X=6 INCHES AND Y=8 INCHES. THE PUNCH CARDS ARE THEN USED
CC  TO CALCULATE ELASTIC MODULI DATA VIA PROGRAM ELASMOD. THE PROGRAM
CC  IS CAPABLE OF HANDLING ANY NUMBER OF EXPERIMENTS OR RUNS PER EXPER.
CC  THE SUFFIX OR PREFIX OF 0 ON A VARIABLE REFERS TO THE INITIAL STATE
CC  OF THAT VARIABLE, THE SUFFIX 1 ON A VARIABLE REFERS TO AN AXIAL
CC  MEASUREMENT, THE SUFFIX 2 REFERS TO RADIAL, I.E. CIRCUMFERENTIAL,
CC  MEASUREMENT. RMAN= MANGANIN CELL RESISTANCE, R1 AND R2= STRAIN GAGE
CC  RESISTANCES, DL1 AND DL2= CALCULATED LINEAR STRAIN,   DV= VOLUME
CC  STRAIN, SVOL= SPECIFIC VOLUME, DELAY = OBSERVED FIRST ARRIVAL IN
CC  MICROSECONDS, P=PRESSURE, VEL= CALCULATED VELOCITY, DENO  OLEN  DIA
CC  WGT = INITIAL DENSITY  LENGTH  DIAMETER  WEIGHT. PFAC= MANGANIN CELL
CC  FACTOR, GFAC= STRAIN GAGE FACTOR, DLSTU= IRON STANDARD CORRECTION
CC  FACTORS.
000003      DIMENSION RMAN(60),R1(60),R2(60),DELAY(60),P(60),DL1(60),DL2(60),
           CDV(60),VEL(60),NAME(6),XLEN(60),SVOL(60)
000003 1000 READ 9, (EXPID)
000011      READ 1, (RMANO, R10, R20, PFAC, GFAC, OLEN, DIA, WGT)
000035      READ 13, (WGTH2O)
CC  CALCULATE VOLUME AND DENSITY
000043      VOL=(.7854*(DIA**2)*OLEN)/1000.
000047      DENO=WGT/VOL
000050      SVOL(1)=1.0/DENO
000052      WDEN=(WGT-WGTH2O)/VOL
000055      READ 8, (NAME)
000063 1001 PRINT 5
000067      PRINT 6
000073      PRINT 9, (EXPID)
000101      PRINT 8, (NAME)
000107      PRINT 6
000113      PRINT 7, (OLEN, DIA, WGT, DENO,WGTH2O,WDEN,SVOL(1))
000135      PRINT 6
000141      PRINT 4
000145      PRINT 6
000151      READ 11, (NDATA)
000157      DO 100 I=1,NDATA
CC  READ INPUT DATA
000161      READ 2,(RMAN(I),R1(I),R2(I),DELAY(I))
CC  CALCULATE PRESSURE
000174      P(I)=((RMAN(I)-RMANO)/PFAC)*1000.
CC  CALCULATE THE IRON STANDARD CORRECTION FACTORS AT PRESSURE
```

```
000201          DLSTD1=-0.144E-07*P(I)-4.23E-13*P(I)**2
000204          DLSTD2=-0.634E-07*P(I)-4.23E-13*P(I)**2
       CC  CALCULATE LINEAR AND VOLUME STRAIN
000210          IF (R1(I).EQ.0.0) GO TO 101
000212          DL1(I)=((R1(I)-R10)/(GFAC*R10))-DLSTD1
000217          GO TO 102
000220      101 CONTINUE
000220          DL1(I)=  .0
000222      102 IF (R2(I).EQ.0.0) GO TO 103
000224          DL2(I)=((R2(I)-R20)/(GFAC*R20))-DLSTD2
000231          GO TO 104
000231      103 CONTINUE
000231          DL2(I)=  .0
000233      104 IF (DL1(I).EQ. 0.0) GO TO 105
000235          IF (DL2(I).EQ. 0.0) GO TO 105
000236          DV(I)=DL1(I)+2.*DL2(I)
       CC  CALCULATE SPECIFIC VOLUME
000241          SVOL(I)=(VOL*(1.+DV(I)))/WGT
000245          GO TO 106
000246      105 CONTINUE
000246          DV(I)=  .0
000250          SVOL(I)=  .0
000251      106 CONTINUE
000251          XLEN(I)=OLEN*(1.+DL1(I))
       CC  CALCULATE VELOCITY
000255          IF (DELAY(I).EQ.0.0) GO TO 107
000256          VEL(I)=XLEN(I)/(DELAY(I)-0.55)
000261          GO TO 108
000261      107 CONTINUE
000261          VEL(I)=  .0
       CC  PRINT DATA
000263      108 PRINT  3,(P(I),DL1(I),DL2(I),DV(I),XLEN(I),VEL(I),SVOL(I))
000305          PUNCH 10,(EXPID,DL1(I),DL2(I),DV(I),P(I),XLEN(I),VEL(I))
000327      100 CONTINUE
000332          PRINT 6
000335          PRINT 12
000341          READ 11, (NI)
000347          IF (NI) 1000,1001,1002
000351     1002 CONTINUE
000351          CALL EXIT
000352        1 FORMAT (8F10.4)
000352        2 FORMAT (4F10.4)
000352        3 FORMAT(5X,F5.0 ,3(F10.6),2(F10.3),F10.5)
000352        4 FORMAT(4X,*PRESSURE*,2X,*DL/LO*,5X,*DL/LO*,5X,*DV/VO*,5X,*LENGTH*,
               C3X,*VELOCITY*,2X,*SPECIFIC*,/,6X,*BARS*,4X,*AXIAL*,5X,*RADIAL*,
               C16X,*MM*,6X,*KM/SEC*,4X,*VOLUME*,/,65X,*CC/GM*)
000352        5 FORMAT (1H1)
000352        6 FORMAT (/)
000352        7 FORMAT (10X,*LENGTH*,F10.4,*MM*,10X,*DIAMETER*,F10.4,*MM*,/,10X,
               C*WEIGHT*,F10.4,*GM*,10X,*DENSITY*,F11.4,*GM/CC*,/,10X,*WGTH2O*,
               CF10.4,*GM*,10X,*DEN W/O H2O*,F7.4,*GM/CC*,/,10X,*SPECIFIC VOLUME*,
               CF10.6,*CC/GM*)
000352        8 FORMAT (5X,6A10)
000352        9 FORMAT (5X,A10)
000352       10 FORMAT (1A10,2X,3(F10.6),4X,F6.1,2(F10.3))
```

```
000352      11 FORMAT (I2)
000352      12 FORMAT(5X,*0.000 OR 0.0000 MEANS THAT THE VALUE WAS NOT DETERMINED
              C*./,5X,*IN THE EXPERIMENT. 00,0... MEANS THAT ZERO IS DETERMINED*)
000352      13 FORMAT (F10.4)
000352         END
```

EXP1025-4
COMPRESSIONAL VELOCITY-DRY SALEM LIMESTONE

LENGTH 38.2500MM   DIAMETER 25.3000MM
WEIGHT 45.2657GM   DENSITY 2.3540GM/CC
WGTH2O 0.0000GM   DEN W/O H2O 2.3540GM/CC
SPECIFIC VOLUME 0.424809CC/GM

PRESSURE BARS	DL/LO AXIAL	DL/LO RADIAL	DV/VO	LENGTH MM	VELOCITY KM/SEC	SPECIFIC VOLUME CC/GM
0.	0.000000	0.000000	0.000000	38.250	0.000	0.00000
4.	-0.000004	-0.000004	-0.000011	38.250	3.575	0.42480
67.	-0.000087	-0.000146	-0.000379	38.247	3.883	0.42465
161.	-0.000205	-0.000307	-0.000819	38.242	4.047	0.42446
270.	-0.000327	-0.000482	-0.001291	38.237	0.000	0.42426
372.	-0.000413	-0.000614	-0.001642	38.234	4.607	0.42411
484.	-0.000527	-0.000790	-0.002106	38.230	4.662	0.42391
593.	-0.000633	-0.000965	-0.002563	38.226	4.690	0.42372
702.	-0.000731	-0.001136	-0.003004	38.222	4.690	0.42353
800.	-0.000833	-0.001324	-0.003482	38.218	4.718	0.42333
993.	-0.000998	-0.001672	-0.004343	38.212	4.899	0.42296
888.	-0.000876	-0.001533	-0.003941	38.216	4.931	0.42314
804.	-0.000797	-0.001451	-0.003699	38.219	4.887	0.42324
607.	-0.000581	-0.001210	-0.003001	38.228	4.870	0.42353
407.	-0.000345	-0.000957	-0.002259	38.237	4.810	0.42385
214.	-0.000089	-0.000684	-0.001456	38.247	4.636	0.42419
123.	0.000050	-0.000531	-0.001013	38.252	4.511	0.42438
32.	0.000180	-0.000363	-0.000545	38.257	4.136	0.42458
21.	0.000184	-0.000347	-0.000511	38.257	3.944	0.42459

0.000 OR 0.0000 MEANS THAT THE VALUE WAS NOT DETERMINED IN THE EXPERIMENT. 00.0... MEANS THAT ZERO IS DETERMINED

EXP1025-4
COMPRESSIONAL VELOCITY-DRY SALEM LIMESTONE

LENGTH 38.2500MM DIAMETER 25.3000MM
WEIGHT 45.2657GM DENSITY 2.3540GM/CC
WGTH2O 0.0000GM DEN W/O H2O 2.3540GM/CC
SPECIFIC VOLUME 0.000000CC/GM

PRESSURE BARS	DL/LO AXIAL	DL/LO RADIAL	DV/VC	LENGTH MM	VELOCITY KM/SEC	SPECIFIC VOLUME CC/GM
11.	0.000168	-0.000364	-0.000560	38.256	4.323	0.42457
84.	0.000049	-0.000510	-0.000971	38.252	4.474	0.42440
281.	-0.000203	-0.000791	-0.001785	38.242	4.664	0.42405
477.	-0.000447	-0.001075	-0.002598	38.233	4.809	0.42371
733.	-0.000735	-0.001388	-0.003511	38.222	4.900	0.42332
982.	-0.000994	-0.001709	-0.004412	38.212	4.931	0.42294
1470.	-0.001588	-0.002740	-0.007067	38.189	4.960	0.42181
2018.	-0.003186	-0.004666	-0.012518	38.128	4.965	0.41949
2509.	-0.005961	-0.007594	-0.021149	38.022	5.208	0.41583
3039.	-0.008954	-0.010809	-0.030572	37.908	5.123	0.41182
4039.	-0.014685	-0.016422	-0.047528	37.688	5.308	0.40462
5056.	-0.018062	-0.020610	-0.059282	37.559	5.350	0.39963
4032.	-0.017344	-0.019787	-0.056918	37.587	5.316	0.40063
3032.	-0.016528	-0.018993	-0.054515	37.618	5.276	0.40165
1930.	-0.015394	-0.017790	-0.050973	37.661	5.124	0.40316
1070.	-0.014211	-0.016549	-0.047310	37.706	4.696	0.40471
495.	-0.013060	-0.015278	-0.043616	37.750	4.415	0.40628
147.	-0.011598	-0.013525	-0.038648	37.806	3.618	0.40839
42.	-0.010926	-0.012473	-0.035873	37.832	0.000	0.40957

0.000 OR 0.0000 MEANS THAT THE VALUE WAS NOT DETERMINED IN THE EXPERIMENT. 00.0... MEANS THAT ZERO IS DETERMINED

EXP1025-4
COMPRESSIONAL VELOCITY-DRY SALEM LIMESTONE

LENGTH 38.2500MM DIAMETER 25.3000MM
WEIGHT 45.2657GM DENSITY 2.3540GM/CC
WGTH2O 0.0000GM DEN W/O H2O 2.3540GM/CC
SPECIFIC VOLUME 0.424571CC/GM

PRESSURE BARS	DL/LO AXIAL	DL/LO RADIAL	DV/VO	LENGTH MM	VELOCITY KM/SEC	SPECIFIC VOLUME CC/GM
42.	-0.010926	-0.012473	-0.035873	37.832	0.000	0.40957
474.	-0.012231	-0.014598	-0.041427	37.782	4.085	0.40721
982.	-0.013312	-0.015635	-0.044583	37.741	4.547	0.40587
1982.	-0.014819	-0.017255	-0.049329	37.683	5.058	0.40385
3021.	-0.016066	-0.018602	-0.053269	37.635	5.156	0.40218
4004.	-0.017041	-0.019658	-0.056358	37.598	5.410	0.40087
5042.	-0.018099	-0.020785	-0.059669	37.558	5.327	0.39946
6014.	-0.019156	-0.021853	-0.062861	37.517	5.398	0.39811
6986.	-0.020205	-0.022868	-0.065940	37.477	5.431	0.39680
5902.	-0.019541	-0.022165	-0.063872	37.503	5.451	0.39768
5049.	-0.018975	-0.021569	-0.062114	37.524	5.438	0.39842
4007.	-0.018205	-0.020795	-0.059796	37.554	5.388	0.39941
2958.	-0.017354	-0.019993	-0.057340	37.586	5.316	0.40045
2091.	-0.016539	-0.019142	-0.054824	37.617	5.049	0.40152
1119.	-0.015395	-0.017993	-0.051380	37.661	4.708	0.40298
565.	-0.014371	-0.016827	-0.048025	37.700	4.212	0.40441
67.	-0.012197	-0.013871	-0.039939	37.783	0.000	0.40784

0.000 OR 0.0000 MEANS THAT THE VALUE WAS NOT DETERMINED
IN THE EXPERIMENT. 00.0... MEANS THAT ZERO IS DETERMINED

EXP1025-9
SHEAR VELOCITY - DRY SALEM LIMESTONE

LENGTH 39.9000MM DIAMETER 25.3000MM
WEIGHT 47.3000GM DENSITY 2.3581GM/CC
WGTH2O 0.0000GM DEN W/O H2O 2.3581GM/CC
SPECIFIC VOLUME 0.424076CC/GM

PRESSURE BARS	DL/LO AXIAL	DL/LO RADIAL	DV/VO	LENGTH MM	VELOCITY KM/SEC	SPECIFIC VOLUME CC/GM
0.	0.000000	0.000000	0.000000	39.900	0.000	0.00000
89.	-0.000173	-0.000316	-0.000804	39.893	0.000	0.42373
217.	-0.000338	-0.000561	-0.001461	39.887	0.000	0.42346
291.	-0.000468	-0.000786	-0.002041	39.881	0.000	0.42321
405.	-0.000597	-0.001005	-0.002608	39.876	2.650	0.42297
497.	-0.000687	-0.001130	-0.002948	39.873	2.731	0.42283
497.	-0.000687	-0.001130	-0.002948	39.873	2.731	0.42283
714.	-0.000934	-0.001521	-0.003976	39.863	2.703	0.42239
835.	-0.001051	-0.001680	-0.004410	39.858	2.693	0.42221
945.	-0.001165	-0.001831	-0.004827	39.854	2.702	0.42203
1034.	-0.001286	-0.001988	-0.005262	39.849	2.720	0.42184
934.	-0.001177	-0.001840	-0.004856	39.853	2.702	0.42202
835.	-0.001075	-0.001703	-0.004482	39.857	2.693	0.42218
750.	-0.000969	-0.001594	-0.004157	39.861	2.693	0.42231
632.	-0.000860	-0.001470	-0.003801	39.866	2.694	0.42246
533.	-0.000758	-0.001390	-0.003537	39.870	2.676	0.42258
426.	-0.000625	-0.001234	-0.003092	39.875	2.676	0.42276
323.	-0.000495	-0.001094	-0.002683	39.880	2.659	0.42294
217.	-0.000358	-0.000942	-0.002242	39.886	2.650	0.42313
128.	-0.000212	-0.000781	-0.001774	39.892	2.642	0.42332
39.	-0.000015	-0.000513	-0.001041	39.899	0.000	0.42363

0.000 OR 0.0000 MEANS THAT THE VALUE WAS NOT DETERMINED IN THE EXPERIMENT. 00.0... MEANS THAT ZERO IS DETERMINED

EXP1025-9
SHEAR VELOCITY - DRY SALEM LIMESTONE

LENGTH	39.9000MM	DIAMETER	25.3000MM
WEIGHT	47.3000GM	DENSITY	2.3581GM/CC
WGTH2O	0.0000GM	DEN W/O H2O	2.3581GM/CC

SPECIFIC VOLUME 0.000000CC/GM

PRESSURE BARS	DL/LO AXIAL	DL/LO RADIAL	DV/VO	LENGTH MM	VELOCITY KM/SEC	SPECIFIC VOLUME CC/GM
39.	-0.000015	-0.000513	-0.001041	39.899	0.000	0.42363
504.	-0.000699	-0.001387	-0.003474	39.872	0.000	0.42260
991.	-0.001275	-0.002022	-0.005320	39.849	0.000	0.42182
1520.	-0.002061	-0.002876	-0.007814	39.818	0.000	0.42076
2032.	-0.003656	-0.004608	-0.012872	39.754	0.000	0.41862
1872.	-0.003524	-0.004392	-0.012308	39.759	0.000	0.41886
2064.	-0.003735	-0.004637	-0.013010	39.751	0.000	0.41856
2533.	-0.006315	-0.007259	-0.020834	39.648	0.000	0.41524
3094.	-0.009084	-0.010046	-0.029175	39.538	0.000	0.41170
2881.	-0.009143	-0.009905	-0.028953	39.535	0.000	0.41180
3091.	-0.009385	-0.010204	-0.029794	39.526	0.000	0.41144
4206.	-0.014303	-0.015277	-0.044857	39.329	0.000	0.40505
3982.	-0.014260	-0.015074	-0.044407	39.33[illegible]	0.000	0.40524
4266.	-0.014536	-0.015301	-0.045138	39.320	0.000	0.40493
5332.	-0.015850	-0.016708	-0.049266	39.268	0.000	0.40318
5012.	-0.015697	-0.016408	-0.048514	39.274	0.000	0.40350
5389.	-0.015960	-0.016708	-0.049376	39.263	0.000	0.40314
6380.	-0.017052	-0.017762	-0.052577	39.220	0.000	0.40178
5794.	-0.016746	-0.017311	-0.051368	39.232	0.000	0.40229
6217.	-0.017000	-0.017670	-0.052341	39.222	0.000	0.40188
6742.	-0.017402	-0.018078	-0.053559	39.206	0.000	0.40136
6007.	-0.017036	-0.017558	-0.052152	39.220	0.000	0.40196
4337.	-0.015972	-0.016156	-0.048284	39.263	0.000	0.40360
3012.	-0.014888	-0.015166	-0.045220	39.306	0.000	0.40490
2156.	-0.014100	-0.014425	-0.042950	39.337	0.000	0.40586
1560.	-0.013352	-0.013766	-0.040884	39.367	0.000	0.40674
1080.	-0.012553	-0.012956	-0.038466	39.399	0.000	0.40776
575.	-0.010303	-0.010193	-0.030689	39.489	0.000	0.41106
536.	-0.009966	-0.009898	-0.029763	39.502	0.000	0.41145
337.	-0.009687	-0.009554	-0.028796	39.513	0.000	0.41186
28.	-0.009426	-0.009173	-0.027773	39.524	0.000	0.41230

0.000 OR 0.0000 MEANS THAT THE VALUE WAS NOT DETERMINED IN THE EXPERIMENT. 00.0... MEANS THAT ZERO IS DETERMINED

EXP1025-10
COMPRESSIONAL VELOCITY - DRY BEREA SANDSTONE

LENGTH 40.0000MM DIAMETER 25.2700MM
WEIGHT 43.3000GM DENSITY 2.1584GM/CC
WGTH2O 0.0000GM DEN W/O H2O 2.1584GM/CC
SPECIFIC VOLUME 0.463312CC/GM

PRESSURE BARS	DL/LO AXIAL	DL/LO RADIAL	DV/VO	LENGTH MM	VELOCITY KM/SEC	SPECIFIC VOLUME CC/GM
0.	0.000000	0.000000	0.000000	40.000	2.360	0.00000
96.	-0.000819	-0.000835	-0.002490	39.967	3.431	0.46216
209.	-0.001486	-0.001434	-0.004355	39.941	3.681	0.46129
298.	-0.001901	-0.001919	-0.005740	39.924	3.895	0.46065
387.	-0.002208	-0.002317	-0.006841	39.912	3.983	0.46014
508.	-0.002511	-0.002720	-0.007950	39.900	0.000	0.45963
596.	-0.002745	-0.003061	-0.008867	39.890	4.050	0.45920
710.	-0.002936	-0.003357	-0.009650	39.883	4.091	0.45884
813.	-0.003122	-0.003669	-0.010461	39.875	4.111	0.45847
916.	-0.003273	-0.003914	-0.011101	39.869	4.132	0.45817
1019.	-0.003448	-0.004195	-0.011837	39.862	4.174	0.45783
916.	-0.003193	-0.003934	-0.011061	39.872	4.166	0.45819
724.	-0.002767	-0.003500	-0.009767	39.889	4.112	0.45879
525.	-0.002270	-0.002986	-0.008242	39.909	4.031	0.45949
341.	-0.001744	-0.002427	-0.006599	39.930	3.934	0.46025
114.	-0.001091	-0.001740	-0.004571	39.956	3.600	0.46119
21.	-0.000544	-0.001072	-0.002687	39.978	2.430	0.46207

0.000 OR 0.0000 MEANS THAT THE VALUE WAS NOT DETERMINED IN THE EXPERIMENT. 00.0... MEANS THAT ZERO IS DETERMINED

EXP1025-10
COMPRESSIONAL VELOCITY - DRY BEREA SANDSTONE

LENGTH 40.0000MM
WEIGHT 43.3000GM
WGTH2O 0.0000GM
SPECIFIC VOLUME 0.000000CC/GM

DIAMETER 25.2700MM
DENSITY 2.1584GM/CC
DEN W/O H20 2.1584GM/CC

PRESSURE BARS	DL/LO AXIAL	DL/LO RADIAL	DV/VO	LENGTH MM	VELOCITY KM/SEC	SPECIFIC VOLUME CC/GM
21.	-0.000544	-0.001072	-0.002687	39.978	2.430	0.46207
64.	-0.000784	-0.001440	-0.003663	39.969	3.167	0.46161
110.	-0.000943	-0.001636	-0.004216	39.962	3.460	0.46136
284.	-0.001549	-0.002323	-0.006195	39.938	3.974	0.46044
490.	-0.002102	-0.002896	-0.007895	39.916	4.000	0.45965
980.	-0.003340	-0.004177	-0.011694	39.866	4.131	0.45789
1505.	-0.003968	-0.005160	-0.014289	39.841	4.185	0.45669
612.	0.000000	0.000000	0.000000	40.000	0.000	0.00000
3049.	0.000000	-0.006699	0.000000	40.000	4.233	0.00000
4043.	0.000000	-0.007602	0.000000	40.000	4.278	0.00000
5027.	0.000000	-0.011516	0.000000	40.000	4.211	0.00000
4998.	0.000000	-0.011913	0.000000	40.000	4.124	0.00000
5552.	0.000000	-0.021890	0.000000	40.000	4.124	0.00000
5030.	0.000000	-0.020889	0.000000	40.000	4.053	0.00000
2890.	0.000000	-0.015663	0.000000	40.000	3.493	0.00000
2066.	0.000000	-0.012913	0.000000	40.000	3.279	0.00000
1100.	0.000000	-0.008632	0.000000	40.000	2.817	0.00000
547.	0.000000	-0.005190	0.000000	40.000	0.000	0.00000
163.	0.000000	-0.001094	0.000000	40.000	0.000	0.00000
32.	0.000000	0.001087	0.000000	40.000	0.000	0.00000

0.000 OR 0.0000 MEANS THAT THE VALUE WAS NOT DETERMINED IN THE EXPERIMENT. 00.0... MEANS THAT ZERO IS DETERMINED

EXP1025-10
COMPRESSIONAL VELOCITY - DRY BEREA SANDSTONE

LENGTH 40.0000MM
WEIGHT 43.3000GM
WGTH2O 0.0000GM
SPECIFIC VOLUME 0.462067CC/GM

DIAMETER 25.2700MM
DENSITY 2.1584GM/CC
DEN W/O H2O 2.1584GM/CC

PRESSURE BARS	DL/LO AXIAL	DL/LO RADIAL	DV/VO	LENGTH MM	VELOCITY KM/SEC	SPECIFIC VOLUME CC/GM
32.	0.000000	0.001087	0.000000	40.000	0.000	0.00000
138.	0.000000	-0.000270	0.000000	40.000	0.000	0.00000
501.	0.000000	-0.004507	0.000000	40.000	0.000	0.00000
1005.	0.000000	-0.007833	0.000000	40.000	0.000	0.00000
983.	0.000000	-0.007683	0.000000	40.000	2.768	0.00000
2038.	0.000000	-0.012301	0.000000	40.000	3.239	0.00000
3010.	0.000000	-0.015739	0.000000	40.000	3.670	0.00000
3958.	0.000000	-0.018903	0.000000	40.000	3.902	0.00000
5016.	0.000000	-0.022525	0.000000	40.000	4.028	0.00000
5939.	0.000000	-0.026355	0.000000	40.000	4.167	0.00000
6631.	0.000000	-0.030375	0.000000	40.000	4.301	0.00000
7675.	0.000000	-0.032600	0.000000	40.000	4.348	0.00000
8321.	0.000000	-0.034377	0.000000	40.000	4.494	0.00000
7291.	0.000000	-0.032818	0.000000	40.000	4.372	0.00000
5889.	0.000000	-0.030087	0.000000	40.000	4.145	0.00000
4050.	0.000000	-0.026191	0.000000	40.000	3.810	0.00000
3099.	0.000000	-0.023694	0.000000	40.000	3.540	0.00000
2137.	0.000000	-0.020674	0.000000	40.000	3.125	0.00000
1299.	0.000000	-0.017111	0.000000	40.000	2.667	0.00000
824.	0.000000	-0.014641	0.000000	40.000	2.305	0.00000
11.	0.000000	0.000000	0.000000	40.000	2.145	0.00000

0.000 OR 0.0000 MEANS THAT THE VALUE WAS NOT DETERMINED IN THE EXPERIMENT. 00.0... MEANS THAT ZERO IS DETERMINED

EXP1025-11
COMPRESSIONAL VELOCITY - DRY BEREA SANDSTONE

LENGTH	40.0000MM	DIAMETER	25.2700MM
WEIGHT	43.3000GM	DENSITY	2.1584GM/CC
WGTH2O	0.0000GM	DEN W/O H2O	2.1584GM/CC

SPECIFIC VOLUME 0.463312CC/GM

PRESSURE BARS	DL/LO AXIAL	DL/LO RADIAL	DV/VO	LENGTH MM	VELOCITY KM/SEC	SPECIFIC VOLUME CC/GM
0.	0.000000	0.000000	0.000000	40.000	2.703	0.00000
89.	-0.000927	-0.000890	-0.002707	39.963	2.993	0.46206
185.	-0.001585	-0.001502	-0.004589	39.937	3.488	0.46119
285.	-0.001969	-0.001962	-0.005892	39.921	3.731	0.46058
381.	-0.002209	-0.002317	-0.006842	39.912	3.765	0.46014
509.	-0.002565	-0.002782	-0.008130	39.897	3.729	0.45955
969.	-0.003490	-0.004267	-0.012024	39.860	3.814	0.45774
1482.	-0.004318	-0.005523	-0.015364	39.827	3.848	0.45619
2052.	-0.004936	-0.006534	-0.018004	39.803	4.020	0.45497
2572.	-0.005406	-0.007303	-0.020012	39.784	3.978	0.45404
3035.	0.000000	-0.007883	0.000000	40.000	3.883	0.00000
3520.	0.000000	-0.008586	0.000000	40.000	3.902	0.00000
4061.	0.000000	-0.009553	0.000000	40.000	3.980	0.00000
4621.	0.000000	-0.010781	0.000000	40.000	3.988	0.00000
5208.	0.000000	-0.017322	0.000000	40.000	3.846	0.00000
5169.	0.000000	-0.019481	0.000000	40.000	3.865	0.00000
5875.	0.000000	-0.024107	0.000000	40.000	3.865	0.00000
6562.	0.000000	-0.028357	0.000000	40.000	3.941	0.00000
7232.	0.000000	-0.030531	0.000000	40.000	4.000	0.00000
6516.	0.000000	-0.029517	0.000000	40.000	3.941	0.00000
6113.	0.000000	-0.028845	0.000000	40.000	3.865	0.00000
5159.	0.000000	-0.027232	0.000000	40.000	3.653	0.00000
4197.	0.000000	-0.025313	0.000000	40.000	3.347	0.00000
3210.	0.000000	-0.023018	0.000000	40.000	2.653	0.00000
2127.	0.000000	-0.019901	0.000000	40.000	0.000	0.00000
1115.	0.000000	-0.015806	0.000000	40.000	0.000	0.00000
559.	0.000000	-0.012449	0.000000	40.000	0.000	0.00000
36.	0.000000	-0.006218	0.000000	40.000	0.000	0.00000
0.	0.000000	-0.006794	0.000000	40.000	0.000	0.00000

0.000 OR 0.0000 MEANS THAT THE VALUE WAS NOT DETERMINED IN THE EXPERIMENT. 00.0... MEANS THAT ZERO IS DETERMINED

EXP1025-11
SHEAR VELOCITY - DRY BEREA SANDSTONE

LENGTH 40.0000MM DIAMETER 25.2700MM
WEIGHT 43.3000GM DENSITY 2.1584GM/CC
WGTH2O 0.0000GM DEN W/O H2O 2.1584GM/CC
SPECIFIC VOLUME 0.463312CC/GM

PRESSURE BARS	DL/LO AXIAL	DL/LO RADIAL	DV/VO	LENGTH MM	VELOCITY KM/SEC	SPECIFIC VOLUME CC/GM
0.	0.000000	0.000000	0.000000	40.000	1.351	0.00000
89.	-0.000927	-0.000890	-0.002707	39.963	2.126	0.46206
185.	-0.001585	-0.001502	-0.004589	39.937	2.349	0.46119
285.	-0.001969	-0.001962	-0.005892	39.921	2.449	0.46058
381.	-0.002209	-0.002317	-0.006842	39.912	2.542	0.46014
509.	-0.002565	-0.002782	-0.008130	39.897	2.549	0.45955
969.	-0.003490	-0.004267	-0.012024	39.860	2.622	0.45774
1482.	-0.004318	-0.005523	-0.015364	39.827	2.629	0.45619
2052.	-0.004936	-0.006534	-0.018004	39.803	2.636	0.45497
2572.	-0.005406	-0.007303	-0.020012	39.784	2.592	0.45404
3035.	-0.005543	-0.007883	-0.021308	39.778	2.591	0.45344
3520.	0.000000	-0.008586	0.000000	40.000	2.606	0.00000
4061.	0.000000	-0.009553	0.000000	40.000	2.581	0.00000
4621.	0.000000	-0.010781	0.000000	40.000	2.556	0.00000
5208.	0.000000	-0.017322	0.000000	40.000	2.446	0.00000
5169.	0.000000	-0.019481	0.000000	40.000	2.446	0.00000
5875.	0.000000	-0.024107	0.000000	40.000	2.477	0.00000
6562.	0.000000	-0.028357	0.000000	40.000	2.572	0.00000
7232.	0.000000	-0.030531	0.000000	40.000	2.581	0.00000
6516.	0.000000	-0.029517	0.000000	40.000	2.516	0.00000
6113.	0.000000	-0.028845	0.000000	40.000	2.469	0.00000
5159.	0.000000	-0.027232	0.000000	40.000	2.323	0.00000
4197.	0.000000	-0.025313	0.000000	40.000	2.235	0.00000
3210.	0.000000	-0.023018	0.000000	40.000	2.078	0.00000
2127.	0.000000	-0.019901	0.000000	40.000	1.818	0.00000
1115.	0.000000	-0.015806	0.000000	40.000	0.000	0.00000
559.	0.000000	-0.012449	0.000000	40.000	0.000	0.00000
36.	0.000000	-0.006218	0.000000	40.000	0.000	0.00000
0.	0.000000	-0.006794	0.000000	40.000	0.000	0.00000

0.000 OR 0.0000 MEANS THAT THE VALUE WAS NOT DETERMINED IN THE EXPERIMENT. 00.0... MEANS THAT ZERO IS DETERMINED

EXP1025-13
COMPRESSIONAL VELOCITY-DRY SALEM LIMESTONE

LENGTH 40.0000MM DIAMETER 25.3000MM
WEIGHT 47.3000GM DENSITY 2.3522GM/CC
WGTH2O 0.0000GM DEN W/O H2O 2.3522GM/CC
SPECIFIC VOLUME 0.425139CC/GM

PRESSURE BARS	DL/LO AXIAL	DL/LO RADIAL	DV/VO	LENGTH MM	VELOCITY KM/SEC	SPECIFIC VOLUME CC/GM
0.	0.000000	0.000000	0.000000	40.000	3.960	0.00000
118.	-0.000190	-0.000276	-0.000742	39.992	4.324	0.42482
203.	-0.000296	-0.000511	-0.001318	39.988	4.370	0.42458
314.	-0.000414	-0.000736	-0.001885	39.983	4.394	0.42434
399.	-0.000500	-0.000914	-0.002328	39.980	4.418	0.42415
499.	-0.000618	-0.001104	-0.002826	39.975	4.442	0.42394
581.	-0.000709	-0.001250	-0.003209	39.972	4.466	0.42377
717.	-0.000798	-0.001398	-0.003593	39.968	4.516	0.42361
841.	-0.000904	-0.001541	-0.003987	39.964	4.594	0.42344
920.	-0.000998	-0.001652	-0.004303	39.960	4.674	0.42331
1059.	-0.001112	-0.001763	-0.004639	39.956	0.000	0.42317
1394.	-0.001589	-0.002078	-0.005744	39.936	0.000	0.42270
2036.	-0.003427	-0.002928	-0.009283	39.863	4.089	0.42119
2528.	-0.006097	-0.004523	-0.015142	39.756	5.266	0.41870
3034.	-0.008766	-0.006588	-0.021942	39.649	0.000	0.41581
2988.	-0.009914	-0.007559	-0.025032	39.603	5.316	0.41450
3929.	-0.013572	-0.010938	-0.035448	39.457	5.405	0.41007
4374.	-0.016126	-0.013383	-0.042892	39.355	5.354	0.40690
4902.	-0.017570	-0.014771	-0.047112	39.297	5.535	0.40511
4777.	-0.020298	-0.017454	-0.055206	39.188	5.443	0.40167
5508.	-0.020798	-0.017936	-0.056670	39.168	5.365	0.40105
5996.	-0.021339	-0.018438	-0.058216	39.146	5.363	0.40039
6456.	-0.022485	-0.019530	-0.061546	39.101	5.378	0.39897
7012.	-0.024685	-0.021671	-0.068027	39.013	5.472	0.39622
7647.	-0.025553	-0.022466	-0.070485	38.978	5.414	0.39517
8449.	-0.027345	-0.024409	-0.076162	38.906	5.404	0.39276
8446.	-0.028118	-0.024893	-0.077903	38.875	5.475	0.39202
8075.	-0.027915	-0.024703	-0.077320	38.883	5.492	0.39227
7636.	-0.027669	-0.024458	-0.076584	38.893	5.501	0.39258
7098.	-0.027361	-0.024159	-0.075680	38.906	5.558	0.39296
6043.	-0.026697	-0.023517	-0.073730	38.932	5.562	0.39379
5052.	-0.026078	-0.022900	-0.071879	38.957	5.526	0.39458
3947.	-0.025270	-0.022111	-0.069492	38.989	5.530	0.39560
3201.	-0.024649	-0.021513	-0.067675	39.014	5.441	0.39637
2168.	-0.023603	-0.020477	-0.064557	39.056	5.194	0.39769
1144.	-0.022160	-0.019077	-0.060314	39.114	4.741	0.39950
553.	-0.020898	-0.017799	-0.056497	39.164	3.996	0.40112
364.	-0.020399	-0.017300	-0.054998	39.184	3.697	0.40176

267.	-0.019978	-0.016834	-0.053646	39.201	3.424	0.40233
164.	-0.019410	-0.016209	-0.051828	39.224	3.215	0.40310
43.	-0.018551	-0.015029	-0.048609	39.258	0.000	0.40447

0.000 OR 0.0000 MEANS THAT THE VALUE WAS NOT DETERMINED
IN THE EXPERIMENT. 00.0... MEANS THAT ZERO IS DETERMINED

EXP1025-13
SHEAR VELOCITY-DRY SALEM LIMESTONE

LENGTH	40.0000MM	DIAMETER	25.3000MM
WEIGHT	47.3000GM	DENSITY	2.3522GM/CC
WGTH2O	0.0000GM	DEN W/O H2O	2.3522GM/CC

SPECIFIC VOLUME 0.425139CC/GM

PRESSURE BARS	DL/LO AXIAL	DL/LO RADIAL	DV/VO	LENGTH MM	VELOCITY KM/SEC	SPECIFIC VOLUME CC/GM
0.	0.000000	0.000000	0.000000	40.000	2.632	0.00000
118.	-0.000190	-0.000276	-0.000742	39.992	2.739	0.42482
203.	-0.000296	-0.000511	-0.001318	39.988	2.702	0.42458
314.	-0.000414	-0.000736	-0.001885	39.983	2.729	0.42434
399.	-0.000500	-0.000914	-0.002328	39.980	2.729	0.42415
499.	-0.000618	-0.001104	-0.002826	39.975	2.732	0.42394
581.	-0.000709	-0.001250	-0.003209	39.972	2.701	0.42377
717.	-0.000798	-0.001398	-0.003593	39.968	2.710	0.42361
841.	-0.000904	-0.001541	-0.003987	39.964	2.706	0.42344
920.	-0.000998	-0.001652	-0.004303	39.960	2.709	0.42331
1059.	-0.001112	-0.001763	-0.004639	39.956	2.718	0.42317
1394.	-0.001589	-0.002078	-0.005744	39.936	2.717	0.42270
2036.	-0.003427	-0.002928	-0.009283	39.863	2.740	0.42119
2528.	-0.006097	-0.004523	-0.015142	39.756	2.723	0.41870
3034.	-0.008766	-0.006588	-0.021942	39.649	0.000	0.41581
2988.	-0.009914	-0.007559	-0.025032	39.603	2.809	0.41450
3929.	-0.013572	-0.010938	-0.035448	39.457	2.788	0.41007
4374.	-0.016126	-0.013383	-0.042892	39.355	2.842	0.40690
4902.	-0.017570	-0.014771	-0.047112	39.297	2.868	0.40511
4777.	-0.020298	-0.017454	-0.055206	39.188	2.969	0.40167
5508.	-0.020798	-0.017936	-0.056670	39.168	2.967	0.40105
5996.	-0.021339	-0.018438	-0.058216	39.146	2.966	0.40039
6456.	-0.022485	-0.019530	-0.061546	39.101	2.962	0.39897
7012.	-0.024685	-0.021671	-0.068027	39.013	3.001	0.39622
7647.	-0.025553	-0.022466	-0.070485	38.978	2.991	0.39517
8449.	-0.027345	-0.024409	-0.076162	38.906	2.993	0.39276
8446.	-0.028118	-0.024893	-0.077903	38.875	3.014	0.39202
8075.	-0.027915	-0.024703	-0.077320	38.883	3.014	0.39227
7636.	-0.027669	-0.024458	-0.076584	38.893	3.015	0.39258
7098.	-0.027361	-0.024159	-0.075680	38.906	3.032	0.39296
6043.	-0.026697	-0.023517	-0.073730	38.932	3.025	0.39379
5052.	-0.026078	-0.022900	-0.071879	38.957	3.018	0.39458
3947.	-0.025270	-0.022111	-0.069492	38.989	3.004	0.39560
3201.	-0.024649	-0.021513	-0.067675	39.014	2.980	0.39637
2168.	-0.023603	-0.020477	-0.064557	39.056	2.904	0.39769
1144.	-0.022160	-0.019077	-0.060314	39.114	2.726	0.39950
553.	-0.020898	-0.017799	-0.056497	39.164	2.440	0.40112
364.	-0.020399	-0.017300	-0.054998	39.184	2.325	0.40176

267.	-0.019978	-0.016834	-0.053646	39.201	2.246	0.40233
164.	-0.019410	-0.016209	-0.051828	39.224	2.098	0.40310
43.	-0.018551	-0.015029	-0.048609	39.258	1.711	0.40447

0.000 OR 0.0000 MEANS THAT THE VALUE WAS NOT DETERMINED
IN THE EXPERIMENT. 00.0... MEANS THAT ZERO IS DETERMINED

EXP1025-14
SHEAR VELOCITY-H2O FILLED BEREA SANDSTONE

LENGTH 40.0000MM DIAMETER 25.3000MM
WEIGHT 46.7000GM DENSITY 2.3223GM/CC
WGTH2O 3.4000GM DEN W/O H2O 2.1533GM/CC
SPECIFIC VOLUME 0.430601CC/GM

PRESSURE BARS	DL/LO AXIAL	DL/LO RADIAL	DV/VO	LENGTH MM	VELOCITY KM/SEC	SPECIFIC VOLUME CC/GM
0.	0.000000	0.000000	0.000000	40.000	0.000	0.00000
106.	-0.000239	-0.000234	-0.000708	39.990	0.000	0.43030
209.	-0.000467	-0.000436	-0.001339	39.981	0.000	0.43002
294.	-0.000794	-0.000656	-0.002106	39.968	0.000	0.42969
404.	-0.001066	-0.000862	-0.002789	39.957	0.000	0.42940
596.	-0.001488	-0.001255	-0.003998	39.940	2.309	0.42888
812.	-0.001890	-0.001635	-0.005160	39.924	2.355	0.42838
1050.	-0.002228	-0.002045	-0.006318	39.911	2.403	0.42788
830.	-0.001878	-0.001634	-0.005145	39.925	2.353	0.42839
624.	-0.001492	-0.001221	-0.003934	39.940	0.000	0.42891
337.	-0.000754	-0.000577	-0.001907	39.970	2.227	0.42978
60.	-0.000248	-0.000032	-0.000313	39.990	0.000	0.43047

0.000 OR 0.0000 MEANS THAT THE VALUE WAS NOT DETERMINED IN THE EXPERIMENT. 00.0... MEANS THAT ZERO IS DETERMINED

EXP1025-14
SHEAR VELOCITY-H2O FILLED BEREA SANDSTONE

LENGTH 40.0000MM DIAMETER 25.3000MM
WEIGHT 46.7000GM DENSITY 2.3223GM/CC
WGTH2O 3.4000GM DEN W/O H2O 2.1533GM/CC
SPECIFIC VOLUME 0.000000CC/GM

PRESSURE BARS	DL/LO AXIAL	DL/LO RADIAL	DV/VO	LENGTH MM	VELOCITY KM/SEC	SPECIFIC VOLUME CC/GM
60.	-0.000248	-0.000032	-0.000313	39.990	0.000	0.43047
532.	-0.001060	-0.001066	-0.003193	39.958	0.000	0.42923
990.	-0.002145	-0.002033	-0.006210	39.914	2.403	0.42793
1511.	-0.002931	-0.002826	-0.008584	39.883	2.417	0.42690
2040.	-0.003585	-0.003692	-0.010968	39.857	2.423	0.42588
2554.	-0.004127	-0.004461	-0.013049	39.835	2.441	0.42498
3061.	-0.004608	-0.005114	-0.014836	39.816	2.461	0.42421
4104.	-0.005444	-0.006378	-0.018201	39.782	2.486	0.42276
5144.	-0.005987	-0.007316	-0.020620	39.761	2.524	0.42172
6179.	-0.006638	-0.008326	-0.023289	39.734	2.640	0.42057
7056	-0.007025	-0.009092	-0.025210	39.719	2.675	0.41975
6208.	-0.005698	-0.008011	-0.021719	39.772	2.643	0.42125
5179.	-0.004213	-0.006583	-0.017378	39.831	2.421	0.42312
4165.	0.000000	-0.005182	0.000000	40.000	2.417	0.00000
3100.	0.000000	-0.003526	0.000000	40.000	2.292	0.00000
2132.	0.000000	-0.001991	0.000000	40.000	2.256	0.00000

0.000 OR 0.0000 MEANS THAT THE VALUE WAS NOT DETERMINED IN THE EXPERIMENT. 00.0... MEANS THAT ZERO IS DETERMINED

EXP1025-21
COMP VELOCITY-H2O FILLED SALEM LIMESTONE

LENGTH 38.2000MM DIAMETER 25.2980MM
WEIGHT 46.9520GM DENSITY 2.4453GM/CC
WGTH2O 2.0900GM DEN W/O H2O 2.3364GM/CC
SPECIFIC VOLUME 0.408952CC/GM

PRESSURE BARS	DL/LO AXIAL	DL/LO RADIAL	DV/VO	LENGTH MM	VELOCITY KM/SEC	SPECIFIC VOLUME CC/GM
0.	0.000000	0.000000	0.000000	38.200	4.489	0.00000
99.	-0.000159	-0.000319	-0.000797	38.194	4.646	0.40863
215.	-0.000294	-0.000541	-0.001375	38.189	4.703	0.40839
475.	-0.000679	-0.001058	-0.002795	38.174	4.802	0.40781
757.	-0.001060	-0.001430	-0.003919	38.160	4.874	0.40735
1024.	-0.001513	-0.001798	-0.005109	38.142	4.878	0.40686
904.	-0.001370	-0.001685	-0.004741	38.148	4.872	0.40701
443.	-0.000735	-0.001169	-0.003073	38.172	4.695	0.40770
264.	-0.000441	-0.000923	-0.002287	38.183	4.589	0.40802
130.	-0.000191	-0.000695	-0.001580	38.193	4.330	0.40831
11.	-0.000232	-0.000337	-0.000906	38.191	4.243	0.40858

0.000 OR 0.0000 MEANS THAT THE VALUE WAS NOT DETERMINED
IN THE EXPERIMENT. 00.0... MEANS THAT ZERO IS DETERMINED

EXP1025-21
COMP VELOCITY-H2O FILLED SALEM LIMESTONE

LENGTH 38.2000MM　　DIAMETER 25.2980MM
WEIGHT 46.9520GM　　DENSITY 2.4453GM/CC
WGTH2O 2.0900GM　　DEN W/O H2O 2.3364GM/CC
SPECIFIC VOLUME 0.000000CC/GM

PRESSURE BARS	DL/LO AXIAL	DL/LO RADIAL	DV/VO	LENGTH MM	VELOCITY KM/SEC	SPECIFIC VOLUME CC/GM
11.	-0.000232	-0.000337	-0.000906	38.191	4.243	0.40858
95.	-0.000436	-0.000560	-0.001556	38.183	4.319	0.40832
289.	-0.000806	-0.000877	-0.002560	38.169	4.522	0.40791
588.	-0.001327	-0.001280	-0.003887	38.149	4.781	0.40736
996.	-0.001938	-0.001776	-0.005490	38.126	4.875	0.40671
1246.	-0.002355	-0.002045	-0.006445	38.110	4.949	0.40632
1583.	-0.003204	-0.002369	-0.007941	38.078	5.064	0.40570
2055.	-0.004027	-0.002760	-0.009546	38.046	5.141	0.40505
3079.	-0.005818	-0.003652	-0.013123	37.978	5.050	0.40359
2987.	-0.005736	-0.003602	-0.012940	37.981	5.057	0.40366
2516.	-0.005302	-0.003224	-0.011750	37.997	5.060	0.40415
2094.	-0.004880	-0.002862	-0.010603	38.014	4.918	0.40462
1214.	-0.004008	-0.002103	-0.008214	38.047	4.750	0.40559
591.	-0.003211	-0.001460	-0.006132	38.077	4.327	0.40644
338.	-0.002870	-0.001179	-0.005229	38.090	4.237	0.40681
137.	-0.002416	-0.000835	-0.004085	38.108	4.089	0.40728
18.	-0.002229	-0.000228	-0.002685	38.115	3.358	0.40785

0.000 OR 0.0000 MEANS THAT THE VALUE WAS NOT DETERMINED
IN THE EXPERIMENT. 00.0... MEANS THAT ZERO IS DETERMINED

EXP1025-21
COMP VELOCITY-H2O FILLED SALEM LIMESTONE

LENGTH	38.2000MM	DIAMETER	25.2980MM
WEIGHT	46.9520GM	DENSITY	2.4453GM/CC
WGTH2O	2.0900GM	DEN W/O H2O	2.3364GM/CC

SPECIFIC VOLUME 0.408582CC/GM

PRESSURE BARS	DL/LO AXIAL	DL/LO RADIAL	DV/VO	LENGTH MM	VELOCITY KM/SEC	SPECIFIC VOLUME CC/GM
28.	-0.002165	-0.000075	-0.002314	38.117	3.388	0.40801
120.	-0.002484	-0.000450	-0.003385	38.105	3.876	0.40757
489.	-0.003453	-0.001246	-0.005946	38.068	4.336	0.40652
1013.	-0.004151	-0.001763	-0.007677	38.041	4.668	0.40581
1527.	-0.004769	-0.002260	-0.009289	38.018	4.806	0.40515
2069.	-0.005422	-0.002747	-0.010915	37.993	4.896	0.40449
3357.	-0.006612	-0.003590	-0.013791	37.947	5.060	0.40331
4039.	-0.008003	-0.004577	-0.017156	37.894	5.121	0.40194
4968.	-0.009017	-0.005366	-0.019748	37.856	5.136	0.40088
6759.	-0.011107	-0.007175	-0.025458	37.776	5.435	0.39854
6499.	-0.010964	-0.007065	-0.025093	37.781	5.421	0.39869
5531.	-0.010321	-0.006460	-0.023242	37.806	5.340	0.39945
4469.	-0.009499	-0.005709	-0.020916	37.837	5.092	0.40040
3019.	-0.008169	-0.004500	-0.017169	37.888	4.748	0.40193
3019.	-0.008241	-0.004556	-0.017353	37.885	4.826	0.40186
2115.	-0.007298	-0.003659	-0.014617	37.921	4.435	0.40297
1119.	-0.006231	-0.002467	-0.011165	37.962	3.934	0.40439
563.	-0.006267	-0.001808	-0.009883	37.961	3.499	0.40491
151.	-0.006221	-0.001529	-0.009279	37.962	3.327	0.40516
35.	-0.006175	-0.001480	-0.009134	37.964	3.259	0.40522

0.000 OR 0.0000 MEANS THAT THE VALUE WAS NOT DETERMINED IN THE EXPERIMENT. 00.0... MEANS THAT ZERO IS DETERMINED

EXP1025-22
COMP VELOCITY-H2O FILLED BEREA SANDSTONE

LENGTH 40.0000MM DIAMETER 25.2980MM
WEIGHT 46.7240GM DENSITY 2.3239GM/CC
WGTH2O 3.4500GM DEN W/O H2O 2.1523GM/CC
SPECIFIC VOLUME 0.430312CC/GM

PRESSURE BARS	DL/LO AXIAL	DL/LO RADIAL	DV/VO	LENGTH MM	VELOCITY KM/SEC	SPECIFIC VOLUME CC/GM
0.	0.000000	0.000000	0.000000	40.000	0.000	0.00000
64.	-0.000811	-0.000714	-0.002239	39.968	3.431	0.42935
160.	-0.001629	-0.001198	-0.004024	39.935	3.877	0.42858
352.	-0.002309	-0.001788	-0.005884	39.908	4.060	0.42778
633.	-0.003088	-0.002576	-0.008241	39.876	4.220	0.42677
942.	-0.003646	-0.003347	-0.010340	39.854	4.240	0.42586
935.	-0.003638	-0.003352	-0.010341	39.854	4.240	0.42586
1351.	-0.004644	-0.004316	-0.013276	39.814	4.249	0.42460
1966.	-0.005763	-0.005665	-0.017093	39.769	4.299	0.42296
2965.	-0.007257	-0.007430	-0.022116	39.710	4.393	0.42079
3448.	-0.007907	-0.008120	-0.024148	39.684	4.434	0.41992
3960.	-0.008597	-0.008857	-0.026311	39.656	4.461	0.41899
4515.	-0.009258	-0.009574	-0.028406	39.630	4.355	0.41809
5009.	-0.009936	-0.010303	-0.030543	39.603	4.357	0.41717
5617.	-0.010760	-0.011161	-0.033082	39.570	4.411	0.41608
6790.	-0.012312	-0.012794	-0.037900	39.508	4.567	0.41400
5851.	-0.011186	-0.011622	-0.034431	39.553	4.546	0.41550
4884.	-0.009882	-0.010320	-0.030522	39.605	4.386	0.41718
3953.	-0.008537	-0.008994	-0.026524	39.659	4.278	0.41890
3011.	-0.007124	-0.007611	-0.022346	39.715	4.194	0.42070
2094.	-0.005636	-0.006138	-0.017913	39.775	4.096	0.42260
1084.	-0.003471	-0.003960	-0.011391	39.861	3.951	0.42541
523.	-0.001784	-0.002218	-0.006221	39.929	3.785	0.42764
14.	-0.000008	0.000141	0.000275	40.000	0.000	0.43043

0.000 OR 0.0000 MEANS THAT THE VALUE WAS NOT DETERMINED
IN THE EXPERIMENT. 00.0... MEANS THAT ZERO IS DETERMINED

EXP1025-22
COMP VELOCITY-H2O FILLED BEREA SANDSTONE

LENGTH	40.0000MM	DIAMETER	25.2980MM
WEIGHT	46.7240GM	DENSITY	2.3239GM/CC
WGTH2O	3.4500GM	DEN W/O H2O	2.1523GM/CC

SPECIFIC VOLUME 0.000000CC/GM

PRESSURE BARS	DL/LO AXIAL	DL/LO RADIAL	DV/VO	LENGTH MM	VELOCITY KM/SEC	SPECIFIC VOLUME CC/GM
4.	-0.000193	-0.000614	-0.001420	39.992	0.000	0.42970
100.	-0.000818	-0.001414	-0.003647	39.967	3.521	0.42874
185.	-0.001251	-0.001846	-0.004944	39.950	3.567	0.42818
473.	-0.002275	-0.002912	-0.008098	39.909	3.878	0.42683
1002.	-0.003818	-0.004499	-0.012816	39.847	3.997	0.42480
3057.	-0.008043	-0.008880	-0.025804	39.678	4.226	0.41921
4956.	-0.010753	-0.011591	-0.033935	39.570	4.339	0.41571
6801.	-0.013151	-0.014122	-0.041395	39.474	4.481	0.41250
5869.	-0.012097	-0.013018	-0.038133	39.516	4.376	0.41390
4053.	-0.009656	-0.010528	-0.030712	39.614	4.214	0.41710
1998.	-0.006461	-0.007280	-0.021022	39.742	4.006	0.42127
1066.	-0.004411	-0.005141	-0.014694	39.824	3.811	0.42399
515.	-0.002656	-0.003278	-0.009212	39.894	3.711	0.42635
142.	-0.001291	-0.001785	-0.004861	39.948	3.615	0.42822
0.	-0.000996	-0.001425	-0.003846	39.960	0.000	0.42866

0.000 OR 0.0000 MEANS THAT THE VALUE WAS NOT DETERMINED IN THE EXPERIMENT. 00.0... MEANS THAT ZERO IS DETERMINED

EXP1025-22
COMP VELOCITY-H2O FILLED BEREA SANDSTONE

LENGTH 40.0000MM DIAMETER 25.2980MM
WEIGHT 46.7240GM DENSITY 2.3230GM/CC
WGTH2O 3.4500GM DEN W/O H2O 2.1523GM/CC
SPECIFIC VOLUME 0.429701CC/GM

PRESSURE BARS	DL/LO AXIAL	DL/LO RADIAL	DV/VO	LENGTH MM	VELOCITY KM/SEC	SPECIFIC VOLUME CC/GM
18.	-0.001076	-0.001741	-0.004558	39.957	0.000	0.42835
124.	-0.001513	-0.002400	-0.006313	39.939	3.260	0.42760
498.	-0.002765	-0.003970	-0.010704	39.889	3.660	0.42571
1031.	-0.004388	-0.005717	-0.015822	39.824	3.866	0.42350
2073.	-0.006858	-0.008323	-0.023504	39.726	3.969	0.42020
3079.	-0.008476	-0.009987	-0.028450	39.661	4.144	0.41807
4085.	-0.009977	-0.011513	-0.033003	39.601	4.199	0.41611
5158.	-0.011440	-0.013010	-0.037460	39.542	4.284	0.41419
6043.	-0.012576	-0.014182	-0.040940	39.497	4.398	0.41269
6733.	-0.013402	-0.015058	-0.043517	39.464	4.395	0.41159
7782.	-0.014722	-0.016421	-0.047565	39.411	4.428	0.40984
6808.	-0.013649	-0.015277	-0.044204	39.454	4.384	0.41129
5699.	-0.012333	-0.013888	-0.040110	39.507	4.290	0.41305
3590.	-0.009411	-0.010920	-0.031251	39.624	4.076	0.41686
2225.	-0.007261	-0.008662	-0.024585	39.710	3.920	0.41973
1660.	-0.006310	-0.007663	-0.021637	39.748	3.870	0.42100
1145.	-0.005149	-0.006424	-0.017998	39.794	3.790	0.42257
622.	-0.003410	-0.004576	-0.012561	39.864	3.657	0.42491
188.	-0.001849	-0.002882	-0.007613	39.926	3.760	0.42704
32.	-0.001462	-0.002105	-0.005672	39.942	0.000	0.42787

0.000 OR 0.0000 MEANS THAT THE VALUE WAS NOT DETERMINED
IN THE EXPERIMENT. 00.0... MEANS THAT ZERO IS DETERMINED

EXP1025-22
COMP VELOCITY-H2O FILLED BEREA SANDSTONE

LENGTH 40.0000MM
WEIGHT 46.7240GM
WGTH2O 3.4500GM
SPECIFIC VOLUME 0.428351CC/GM

DIAMETER 25.2980MM
DENSITY 2.3239GM/CC
DEN W/O H2O 2.1523GM/CC

PRESSURE BARS	DL/LO AXIAL	DL/LO RADIAL	DV/VO	LENGTH MM	VELOCITY KM/SEC	SPECIFIC VOLUME CC/GM
32.	-0.001462	-0.002105	-0.005672	39.942	0.000	0.42787
960.	-0.004505	-0.006031	-0.016567	39.820	3.739	0.42318
3089.	-0.008653	-0.010440	-0.029532	39.654	3.869	0.41760
4852.	-0.011225	-0.013099	-0.037423	39.551	4.073	0.41421
6751.	-0.013658	-0.015590	-0.044839	39.454	4.215	0.41102
5795.	-0.012621	-0.014472	-0.041565	39.495	4.179	0.41243
4095.	-0.010330	-0.012054	-0.034439	39.587	3.999	0.41549
3064.	-0.008810	-0.010453	-0.029716	39.648	3.876	0.41752
970.	-0.005312	-0.006765	-0.018842	39.788	3.708	0.42220
199.	-0.002150	-0.003294	-0.008739	39.914	3.720	0.42655
50.	-0.001638	-0.002284	-0.006207	39.934	0.000	0.42764

0.000 OR 0.0000 MEANS THAT THE VALUE WAS NOT DETERMINED IN THE EXPERIMENT. 00.0... MEANS THAT ZERO IS DETERMINED

EXP1025-23
COMPRESSIONAL VEL DRY WESTERLY GRANITE

LENGTH 41.6000MM DIAMETER 25.3100MM
WEIGHT 55.2700GM DENSITY 2.6407GM/CC
WGTH20 0.0000GM DEN W/O H2O 2.6407GM/CC
SPECIFIC VOLUME 0.378686CC/GM

PRESSURE BARS	DL/LO AXIAL	DL/LO RADIAL	DV/VO	LENGTH MM	VELOCITY KM/SEC	SPECIFIC VOLUME CC/GM
0.	0.000000	0.000000	0.000000	41.600	4.267	0.00000
84.	0.000000	0.000000	0.000000	41.600	4.923	0.00000
186.	0.000000	0.000000	0.000000	41.600	5.306	0.00000
308.	0.000000	0.000000	0.000000	41.600	5.547	0.00000
382.	-0.000257	-0.001065	-0.002386	41.589	5.666	0.37778
515.	-0.000355	-0.001174	-0.002704	41.585	5.720	0.37766
599.	-0.000435	-0.001238	-0.002911	41.582	5.728	0.37758
701.	-0.000522	-0.001337	-0.003196	41.578	5.831	0.37748
813.	-0.000593	-0.001379	-0.003350	41.575	5.856	0.37742
925.	-0.000676	-0.001465	-0.003606	41.572	5.905	0.37732
1009.	-0.000747	-0.001545	-0.003837	41.569	5.964	0.37723
918.	-0.000680	-0.001457	-0.003594	41.572	5.930	0.37732
809.	-0.000609	-0.001371	-0.003351	41.575	5.897	0.37742
715.	-0.000554	-0.001328	-0.003210	41.577	5.864	0.37747
602.	-0.000487	-0.001266	-0.003019	41.580	5.832	0.37754
529.	-0.000379	-0.001153	-0.002685	41.584	5.800	0.37767
420.	-0.000304	-0.001083	-0.002470	41.587	5.760	0.37775
319.	-0.000225	-0.001004	-0.002233	41.591	5.697	0.37784
224.	-0.000150	-0.000912	-0.001975	41.594	5.583	0.37794
133.	-0.000046	-0.000760	-0.001566	41.598	5.266	0.37809
39.	0.000093	-0.000440	-0.000788	41.604	4.474	0.37839
14.	0.000000	0.000000	0.000000	41.600	4.449	0.00000

0.000 OR 0.0000 MEANS THAT THE VALUE WAS NOT DETERMINED IN THE EXPERIMENT. 00.0... MEANS THAT ZERO IS DETERMINED

EXP1025-23
COMPRESSIONAL VEL DRY WESTERLY GRANITE

LENGTH 41.6000MM DIAMETER 25.3100MM
WEIGHT 55.2700GM DENSITY 2.6407GM/CC
WGTH2O 0.0000GM DEN W/O H2O 2.6407GM/CC
SPECIFIC VOLUME 0.000000CC/GM

PRESSURE BARS	DL/LO AXIAL	DL/LO RADIAL	DV/VO	LENGTH MM	VELOCITY KM/SEC	SPECIFIC VOLUME CC/GM
32.	0.000065	-0.000404	-0.000744	41.603	3.731	0.37840
133.	-0.000059	-0.000613	-0.001285	41.598	4.929	0.37820
326.	-0.000265	-0.000906	-0.002077	41.589	5.508	0.37790
441.	-0.000344	-0.000972	-0.002288	41.586	5.650	0.37782
637.	-0.000491	-0.001118	-0.002726	41.580	5.735	0.37765
872.	-0.000657	-0.001261	-0.003179	41.573	5.847	0.37748
1037.	-0.000811	-0.001413	-0.003637	41.566	5.879	0.37731
1545.	-0.001150	-0.001718	-0.004585	41.552	5.894	0.37695
2060.	-0.001485	-0.002001	-0.005487	41.538	6.020	0.37661
2504.	-0.001784	-0.002289	-0.006362	41.526	6.027	0.37628
2942.	-0.002059	-0.002492	-0.007043	41.514	6.034	0.37602
3215.	-0.002232	-0.002636	-0.007504	41.507	6.033	0.37584
3114.	-0.002177	-0.002582	-0.007341	41.509	6.033	0.37591
2630.	-0.001891	-0.002354	-0.006599	41.521	6.026	0.37619
2081.	-0.001565	-0.002057	-0.005678	41.535	5.976	0.37654
1590.	-0.001271	-0.001804	-0.004878	41.547	5.944	0.37684
1065.	-0.000900	-0.001472	-0.003844	41.563	5.870	0.37723
581.	-0.000580	-0.001150	-0.002879	41.576	5.774	0.37760
315.	-0.000399	-0.000996	-0.002390	41.583	5.642	0.37778
119.	-0.000236	-0.000821	-0.001879	41.590	5.360	0.37797
21.	-0.000113	-0.000624	-0.001362	41.595	4.402	0.37817

0.000 OR 0.0000 MEANS THAT THE VALUE WAS NOT DETERMINED IN THE EXPERIMENT. 00.0... MEANS THAT ZERO IS DETERMINED

EXP1025-23
"COMPRESSIONAL VEL DRY WESTERLY GRANITE"

LENGTH	41.6000MM	DIAMETER	25.3100MM
WEIGHT	55.2700GM	DENSITY	2.6407GM/CC
WGTH2O	0.0000GM	DEN W/O H2O	2.6407GM/CC

SPECIFIC VOLUME 0.378686CC/GM

PRESSURE BARS	DL/LO AXIAL	DL/LO RADIAL	DV/VO	LENGTH MM	VELOCITY KM/SEC	SPECIFIC VOLUME CC/GM
21.	-0.000109	-0.000657	-0.001423	41.595	0.000	0.37815
126.	-0.000252	-0.000573	-0.001399	41.589	5.060	0.37816
305.	-0.000456	-0.000854	-0.002164	41.581	5.581	0.37787
515.	-0.000622	-0.001024	-0.002670	41.574	6.017	0.37767
1005.	-0.000970	-0.001403	-0.003775	41.560	6.085	0.37726
2207.	-0.001641	-0.001979	-0.005599	41.532	6.293	0.37657
3040.	-0.002277	-0.002575	-0.007426	41.505	6.356	0.37587
3954.	-0.002818	-0.003055	-0.008927	41.483	6.382	0.37531
4883.	-0.003382	-0.003537	-0.010456	41.459	6.428	0.37473
5793.	-0.003918	-0.003999	-0.011916	41.437	6.424	0.37417
6736.	-0.004468	-0.004642	-0.013751	41.414	6.626	0.37348
7709.	-0.004977	-0.004883	-0.014742	41.393	6.644	0.37310
8207.	-0.005277	-0.005092	-0.015460	41.380	6.653	0.37283
7485.	-0.004893	-0.004744	-0.014381	41.396	6.623	0.37324
6242.	-0.004208	-0.004224	-0.012657	41.425	6.544	0.37389
5475.	-0.003770	-0.003842	-0.011455	41.443	6.589	0.37435
4119.	-0.002976	-0.003133	-0.009242	41.476	6.532	0.37519
3061.	-0.002329	-0.002545	-0.007419	41.503	6.327	0.37588
2105.	-0.001731	-0.002010	-0.005752	41.526	6.321	0.37651
1096.	-0.001049	-0.001397	-0.003843	41.556	6.268	0.37723
550.	-0.000698	-0.001054	-0.002806	41.571	6.016	0.37762
249.	-0.000473	-0.000846	-0.002164	41.580	5.627	0.37787
137.	-0.000385	-0.000678	-0.001742	41.584	5.394	0.37803
39.	-0.000290	-0.000473	-0.001236	41.588	4.401	0.37822

0.000 OR 0.0000 MEANS THAT THE VALUE WAS NOT DETERMINED IN THE EXPERIMENT. 00.0... MEANS THAT ZERO IS DETERMINED

EXP1025-24
COMP VELOCITY H2O FILLED WESTERLY GRANITE

LENGTH 41.0800MM DIAMETER 25.3000MM
WEIGHT 54.6020GM DENSITY 2.6439GM/CC
WGTH2O 0.2400GM DEN W/O H2O 2.6323GM/CC
SPECIFIC VOLUME 0.378228CC/GM

PRESSURE BARS	DL/LO AXIAL	DL/LO RADIAL	DV/VO	LENGTH MM	VELOCITY KM/SEC	SPECIFIC VOLUME CC/GM
7.	0.000000	0.000000	0.000001	41.080	0.000	0.37823
80.	-0.000023	-0.000019	-0.000061	41.079	5.705	0.37820
205.	-0.000054	-0.000052	-0.000157	41.078	5.666	0.37817
302.	-0.000076	-0.000070	-0.000216	41.077	5.674	0.37815
406.	-0.000103	-0.000091	-0.000286	41.076	5.666	0.37812
503.	-0.000122	-0.000118	-0.000357	41.075	5.673	0.37809
603.	-0.000144	-0.000139	-0.000423	41.074	5.673	0.37807
711.	-0.000167	-0.000161	-0.000489	41.073	5.689	0.37804
808.	-0.000186	-0.000175	-0.000536	41.072	5.665	0.37803
894.	-0.000209	-0.000185	-0.000580	41.071	5.704	0.37801
1009.	-0.000235	-0.000215	-0.000664	41.070	5.704	0.37798
804.	-0.000186	-0.000155	-0.000496	41.072	5.681	0.37804
548.	-0.000121	-0.000107	-0.000334	41.075	5.681	0.37810
302.	-0.000069	-0.000066	-0.000200	41.077	5.681	0.37815
107.	-0.000031	-0.000013	-0.000058	41.079	5.412	0.37821
10.	0.000000	0.000017	0.000034	41.080	5.370	0.37824

0.000 OR 0.0000 MEANS THAT THE VALUE WAS NOT DETERMINED
IN THE EXPERIMENT. 00.0... MEANS THAT ZERO IS DETERMINED

EXP1025-24
COMP VELOCITY H2O FILLED WESTERLY GRANITE

LENGTH 41.0800MM DIAMETER 25.3000MM
WEIGHT 54.6020GM DENSITY 2.6439GM/CC
WGTH2O 0.2400GM DEN W/O H2O 2.6323GM/CC
SPECIFIC VOLUME 0.37822CC/GM

PRESSURE BARS	DL/LO AXIAL	DL/LO RADIAL	DV/VO	LENGTH MM	VELOCITY KM/SEC	SPECIFIC VOLUME CC/GM
10.	0.000000	0.000017	0.000034	41.080	5.273	0.37824
107.	-0.000027	-0.000030	-0.000086	41.079	5.301	0.37820
475.	-0.000110	-0.000148	-0.000405	41.075	5.405	0.37807
953.	-0.000220	-0.000206	-0.000632	41.071	5.550	0.37799
1466.	-0.000337	-0.000431	-0.000998	41.066	5.565	0.37785
1979.	-0.000446	-0.000398	-0.001243	41.062	5.610	0.37776
2458.	-0.000559	-0.000492	-0.001544	41.057	5.617	0.37764
2967.	-0.000652	-0.000584	-0.001820	41.053	5.624	0.37754
2565.	-0.000561	-0.000514	-0.001589	41.057	5.609	0.37763
2038.	-0.000449	-0.000415	-0.001278	41.062	5.579	0.37774
1518.	-0.000360	-0.000315	-0.000991	41.065	5.564	0.37785
974.	-0.000236	-0.000201	-0.000637	41.070	5.369	0.37799
520.	-0.000138	-0.000100	-0.000338	41.074	5.232	0.37810
139.	-0.000059	-0.000024	-0.000106	41.078	4.979	0.37819
3.	-0.000024	0.000020	0.000017	41.079	4.979	0.37823

0.000 OR 0.0000 MEANS THAT THE VALUE WAS NOT DETERMINED IN THE EXPERIMENT. 00.0... MEANS THAT ZERO IS DETERMINED

EXP1025-24
COMP VELOCITY H2O FILLED WESTERLY GRANITE

LENGTH	41.0800MM	DIAMETER	25.3000MM
WEIGHT	54.6020GM	DENSITY	2.6439GM/CC
WGTH2O	0.2400GM	DEN W/O H2O	2.6323GM/CC

SPECIFIC VOLUME 0.378241CC/GM

PRESSURE BARS	DL/LO AXIAL	DL/LO RADIAL	DV/VO	LENGTH MM	VELOCITY KM/SEC	SPECIFIC VOLUME CC/GM
7.	-0.000020	0.000021	0.000021	41.079	5.065	0.37824
111.	-0.000055	-0.000017	-0.000089	41.078	5.349	0.37819
475.	-0.000118	-0.000156	-0.000430	41.075	5.334	0.37807
967.	-0.000244	-0.000237	-0.000719	41.070	5.355	0.37796
1497.	-0.000377	-0.000369	-0.001115	41.065	5.432	0.37781
2007.	-0.000490	-0.000477	-0.001445	41.060	5.586	0.37768
2971.	-0.000708	-0.000709	-0.002127	41.051	5.741	0.37742
3924.	-0.000970	-0.000901	-0.002771	41.040	5.700	0.37718
4991.	-0.001213	-0.001124	-0.003461	41.030	5.747	0.37692
5719.	-0.001360	-0.001188	-0.003736	41.024	5.714	0.37682
6662.	-0.001624	-0.001414	-0.004452	41.013	5.777	0.37654
5764.	-0.001444	-0.001217	-0.003878	41.021	5.697	0.37676
4835.	-0.001272	-0.001054	-0.003380	41.028	5.628	0.37695
3920.	-0.001095	-0.000909	-0.002913	41.035	5.583	0.37713
2967.	-0.000894	-0.000705	-0.002305	41.043	5.592	0.37736
2028.	-0.000711	-0.000561	-0.001833	41.051	5.297	0.37753
1470.	-0.000603	-0.000460	-0.001523	41.055	5.263	0.37765
977.	-0.000498	-0.000350	-0.001198	41.060	5.257	0.37778
454.	-0.000397	-0.000230	-0.000856	41.064	5.165	0.37790
101.	-0.000313	-0.000127	-0.000567	41.067	5.102	0.37801
0.	-0.000282	-0.000097	-0.000476	41.068	4.978	0.37805

0.000 OR 0.0000 MEANS THAT THE VALUE WAS NOT DETERMINED IN THE EXPERIMENT. 00.0... MEANS THAT ZERO IS DETERMINED

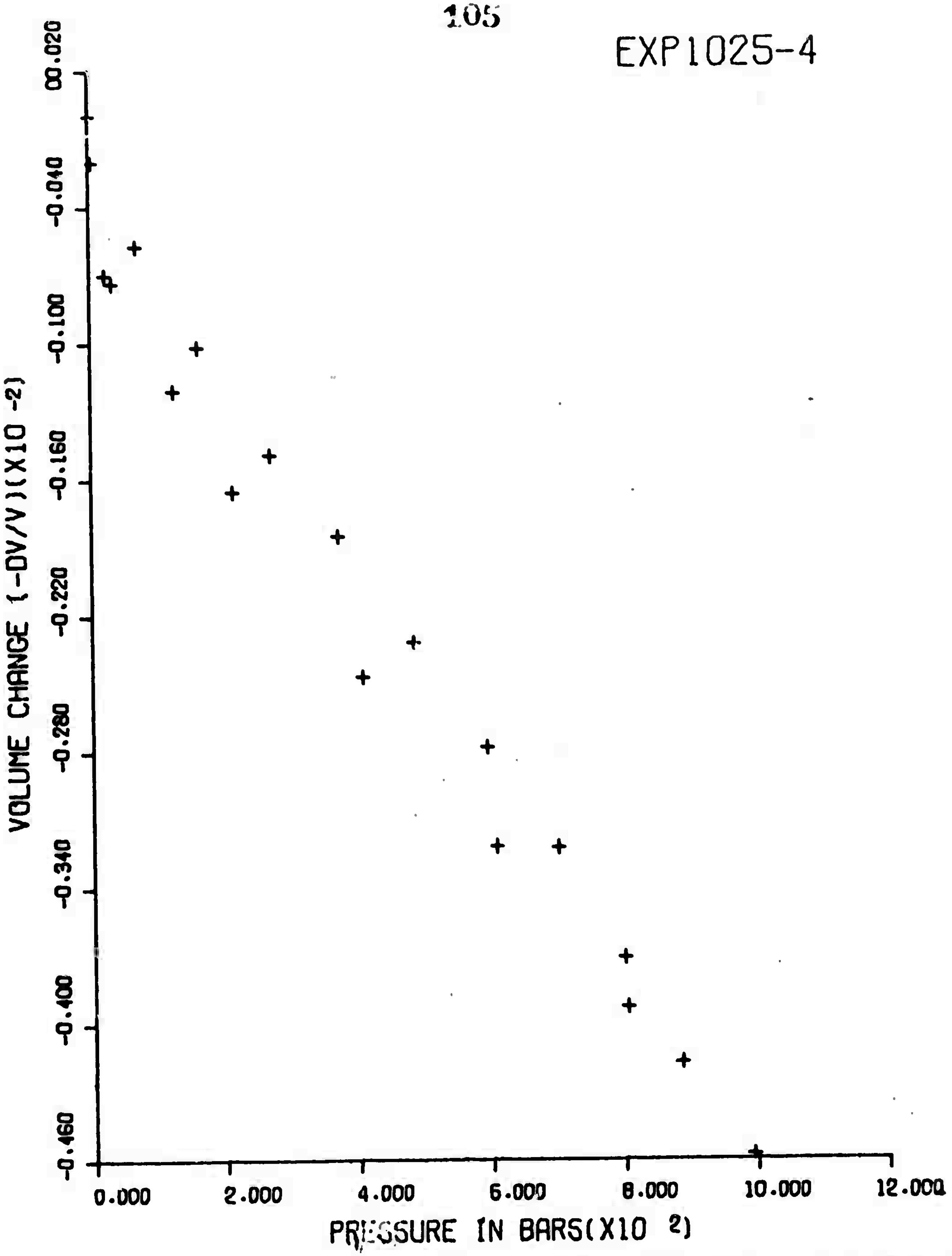
EXP1025-25
SHEAR VELOCITY H2O FILLED BEREA SANDSTONE

LENGTH	40.0000MM	DIAMETER	25.3100MM
WEIGHT	46.7345GM	DENSITY	2.3222GM/CC
WGTH2O	3.4100GM	DEN W/O H2O	2.1528GM/CC
SPECIFIC VOLUME	0.430623CC/GM		

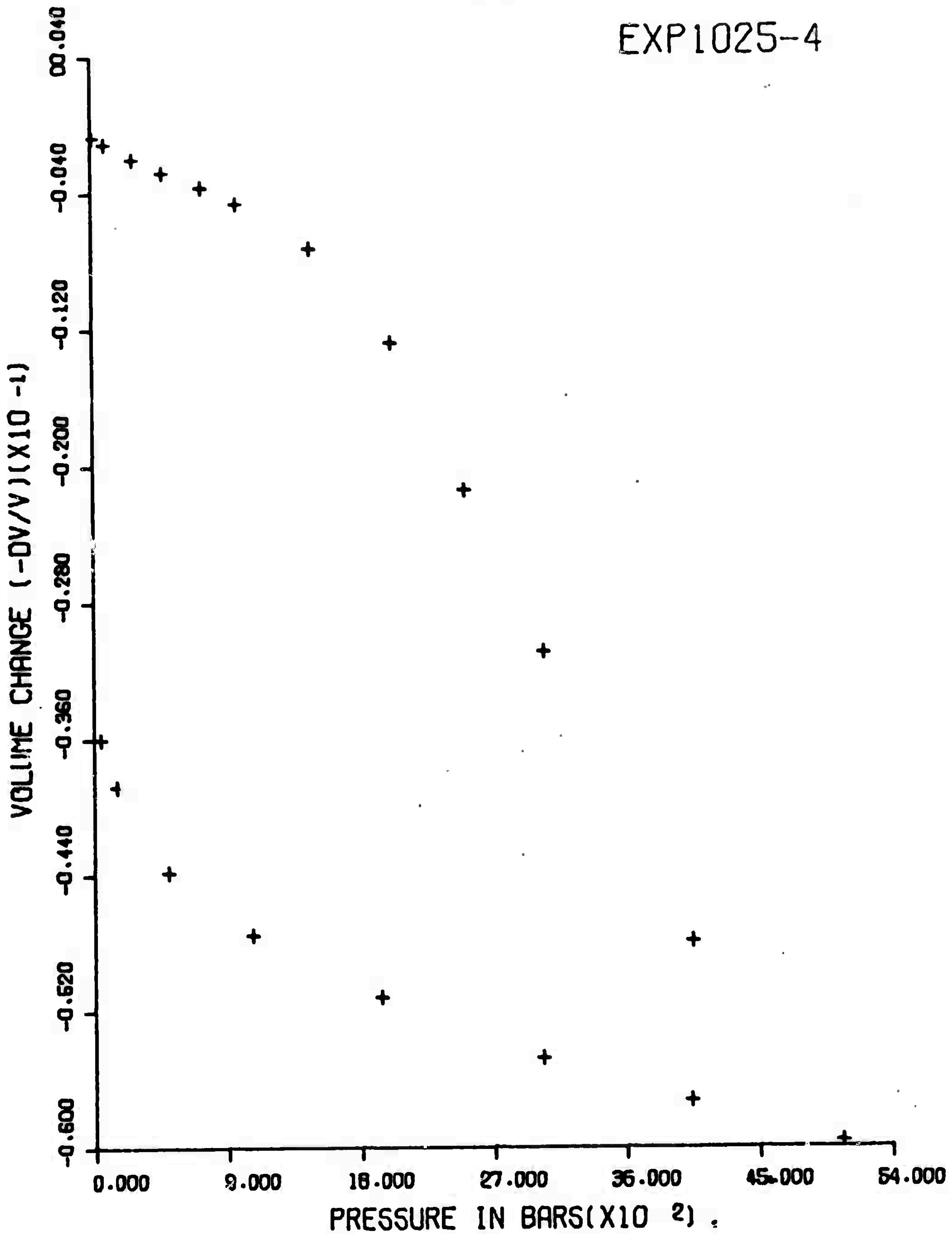
PRESSURE BARS	DL/LO AXIAL	DL/LO RADIAL	DV/VO	LENGTH MM	VELOCITY KM/SEC	SPECIFIC VOLUME CC/GM
3.	-0.000044	0.000016	-0.000012	39.998	2.111	0.43062
76.	-0.000704	-0.000193	-0.001090	39.972	0.000	0.43015
194.	-0.001605	-0.001118	-0.003846	39.936	0.000	0.42897
292.	-0.001991	-0.001402	-0.004795	39.920	2.328	0.42856
372.	-0.002393	-0.001768	-0.005929	39.904	2.354	0.42807
486.	-0.002709	-0.002076	-0.006860	39.892	0.000	0.42767
611.	-0.003050	-0.002419	-0.007887	39.878	2.516	0.42723
712.	-0.003226	-0.002630	-0.008486	39.871	2.523	0.42697
812.	-0.003498	-0.002902	-0.009302	39.860	2.532	0.42662
906.	-0.003751	-0.003179	-0.010108	39.850	2.530	0.42627
997.	-0.003971	-0.003427	-0.010825	39.841	2.539	0.42596
1472.	-0.005088	-0.004571	-0.014229	39.796	2.559	0.42450
1979.	-0.006204	-0.005708	-0.017620	39.752	2.570	0.42304
2802.	-0.007968	-0.007599	-0.023167	39.681	2.611	0.42065
3677.	-0.009896	-0.009644	-0.029183	39.604	2.623	0.41806
4573.	-0.011390	-0.011331	-0.034061	39.544	2.615	0.41596
6608.	-0.014790	-0.015502	-0.045794	39.408	2.502	0.41090
5764.	-0.013767	-0.014475	-0.042716	39.449	2.473	0.41223
4299.	-0.011650	-0.012395	-0.036439	39.534	2.433	0.41493
2983.	-0.009384	-0.010210	-0.029804	39.625	0.000	0.41779
865.	-0.003792	-0.004243	-0.012277	39.848	2.108	0.42534
431.	-0.002130	-0.002370	-0.006869	39.915	2.052	0.42767
66.	-0.000539	-0.000528	-0.001596	39.978	0.000	0.42994
0.	0.000000	0.000234	0.000000	40.000	0.000	0.00000

0.000 OR 0.0000 MEANS THAT THE VALUE WAS NOT DETERMINED IN THE EXPERIMENT. 00.0... MEANS THAT ZERO IS DETERMINED

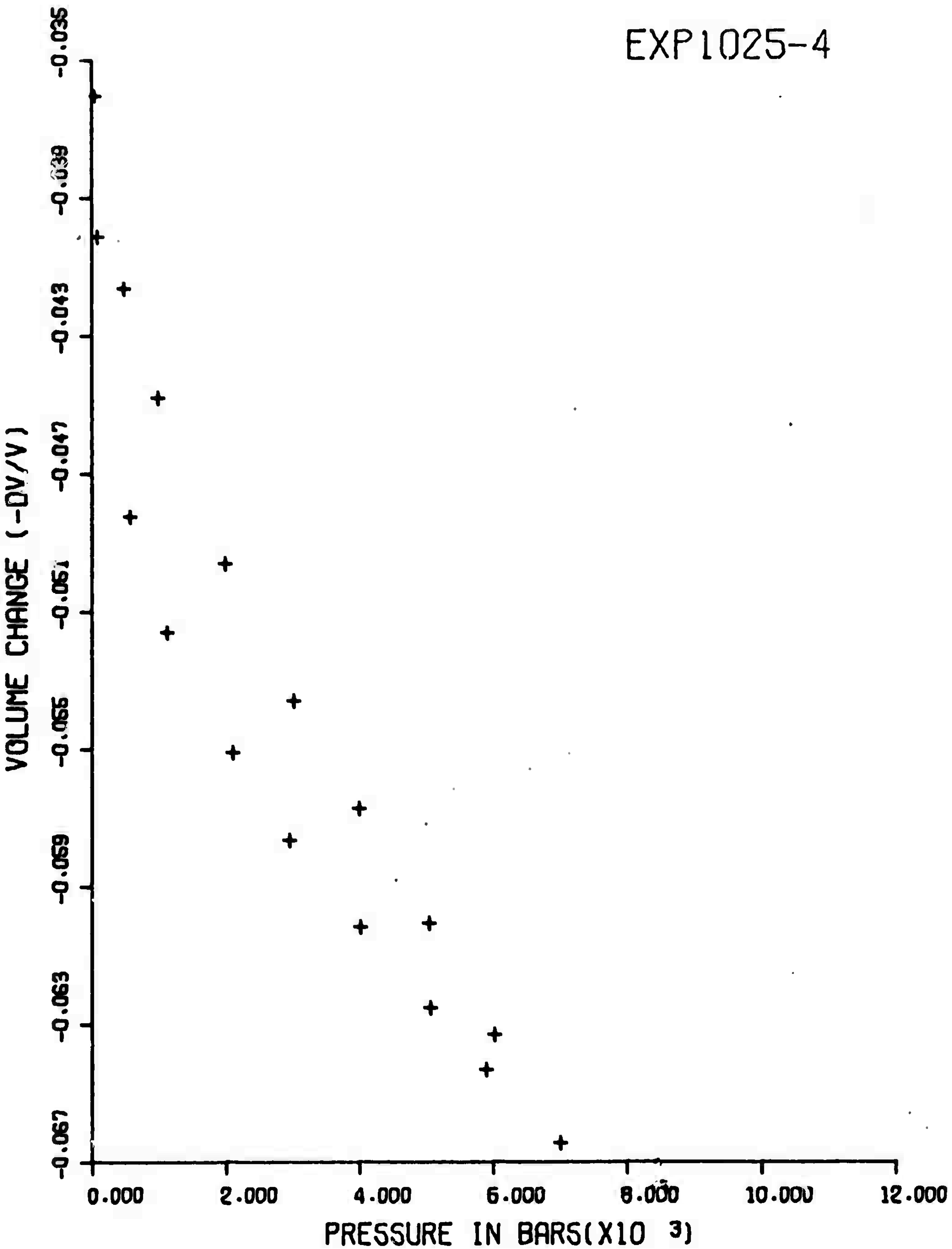
APPENDIX II



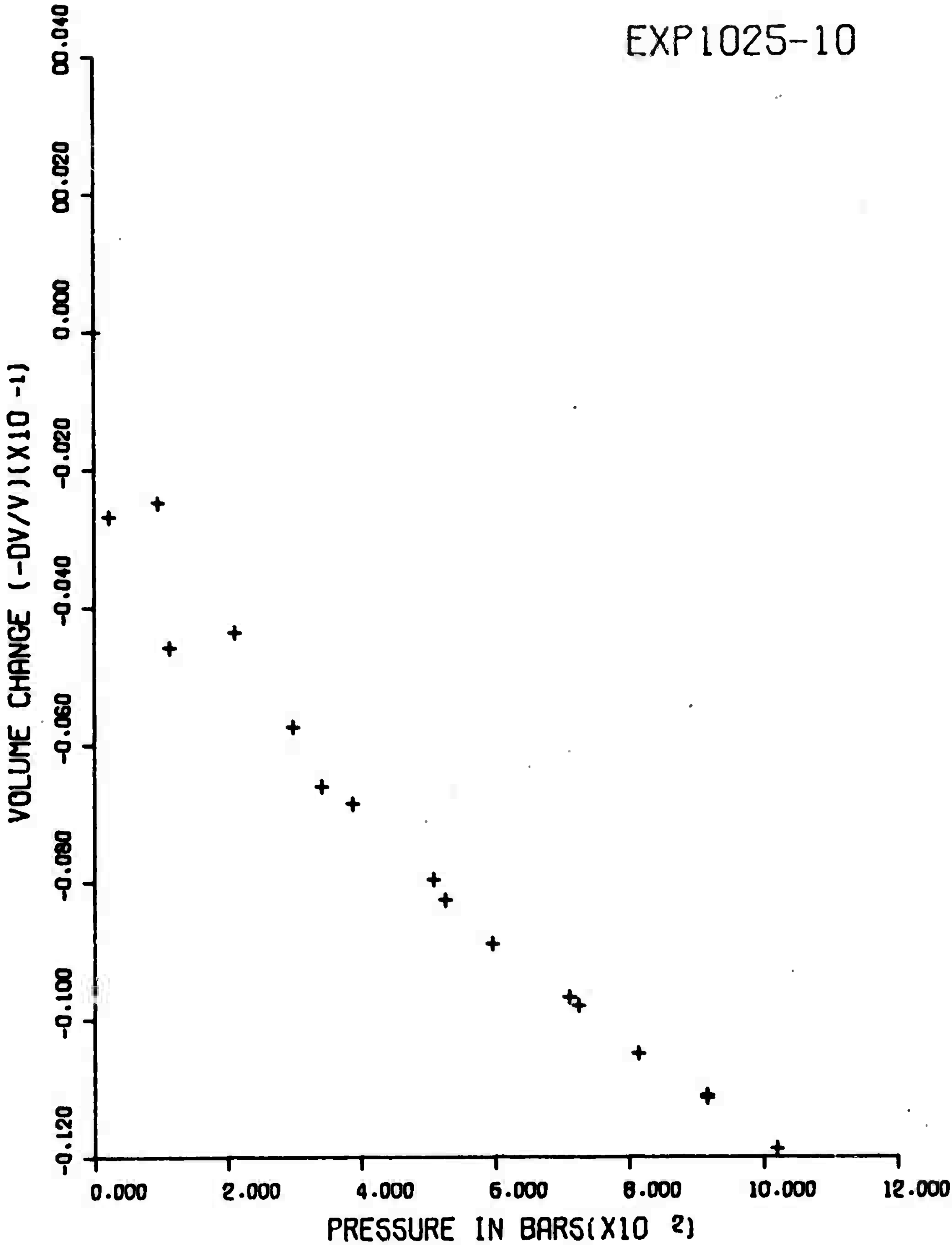
COMPRESSIONAL VELOCITY-DRY SALEM LIMESTONE



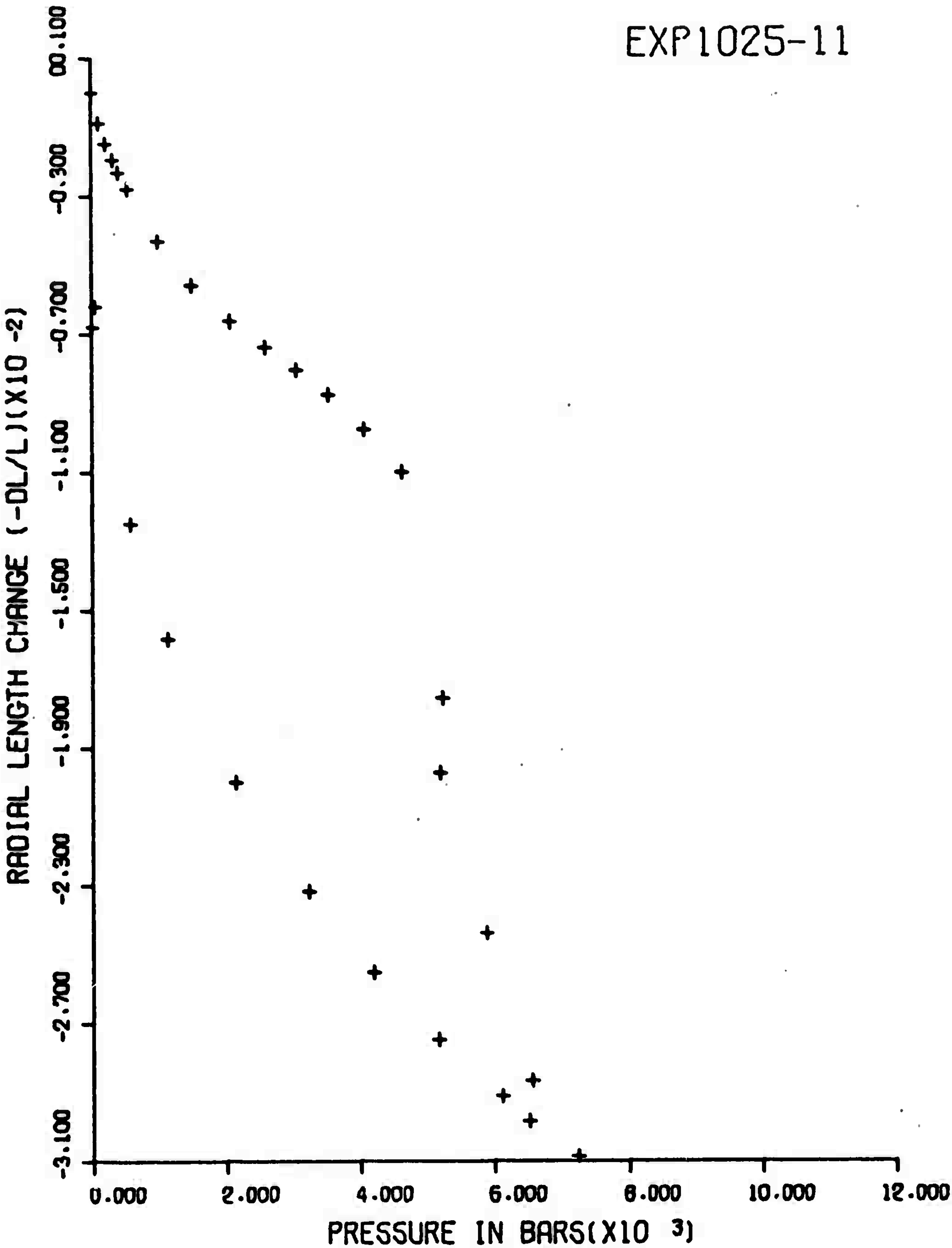
COMPRESSIONAL VELOCITY-DRY SALEM LIMESTONE



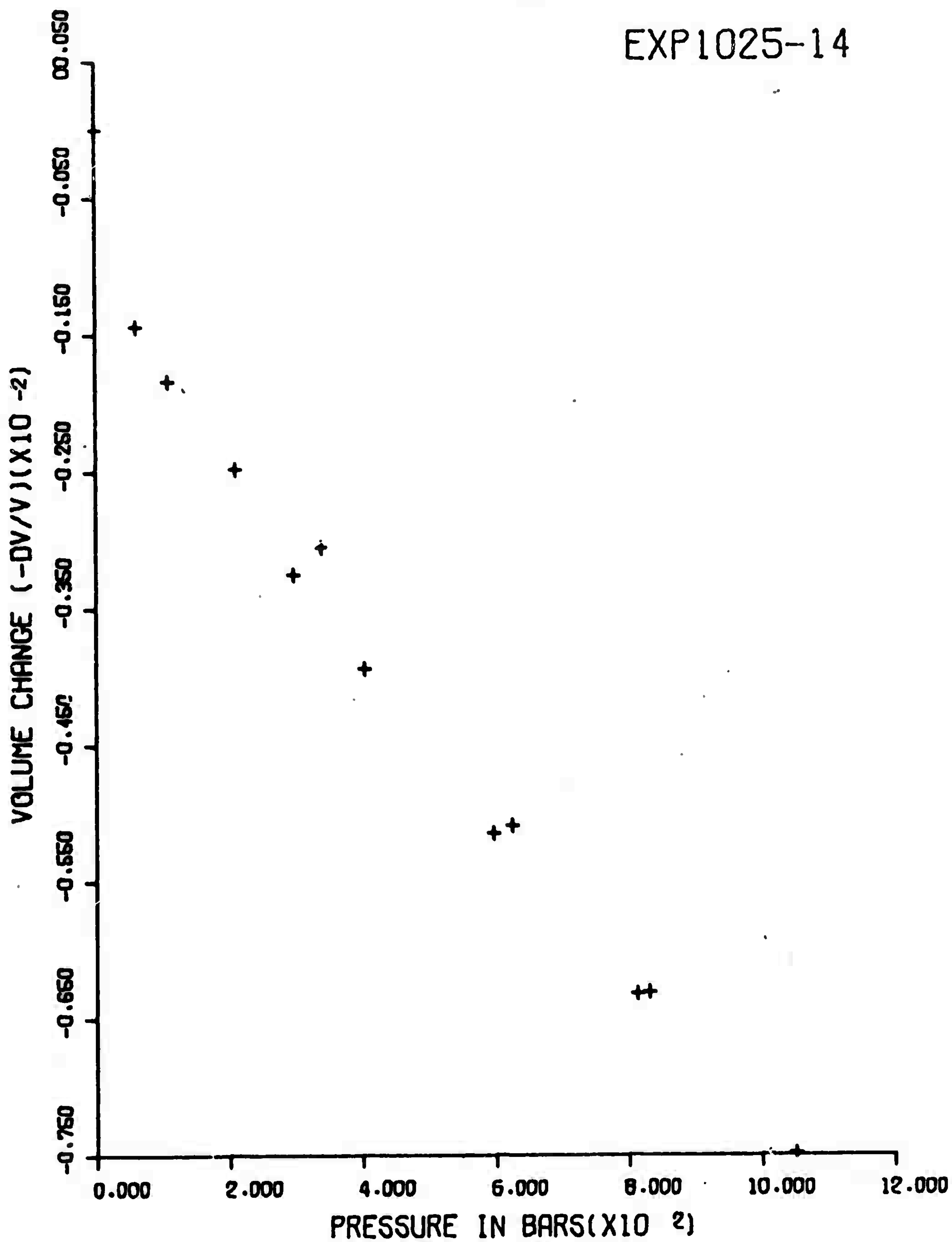
COMPRESSIONAL VELOCITY-DRY SALEM LIMESTONE



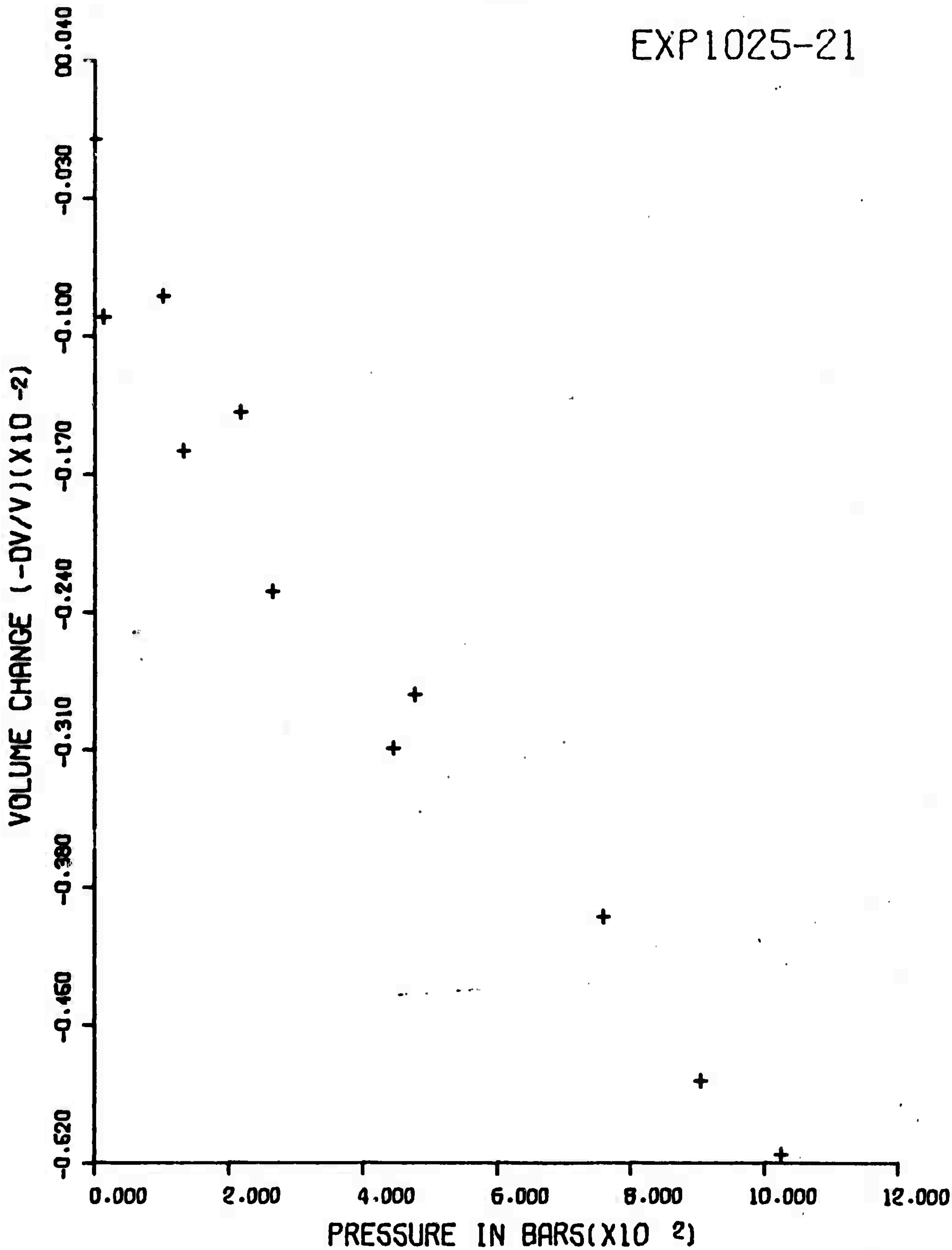
COMPRESSIONAL VELOCITY - DRY BEREA SANDSTONE



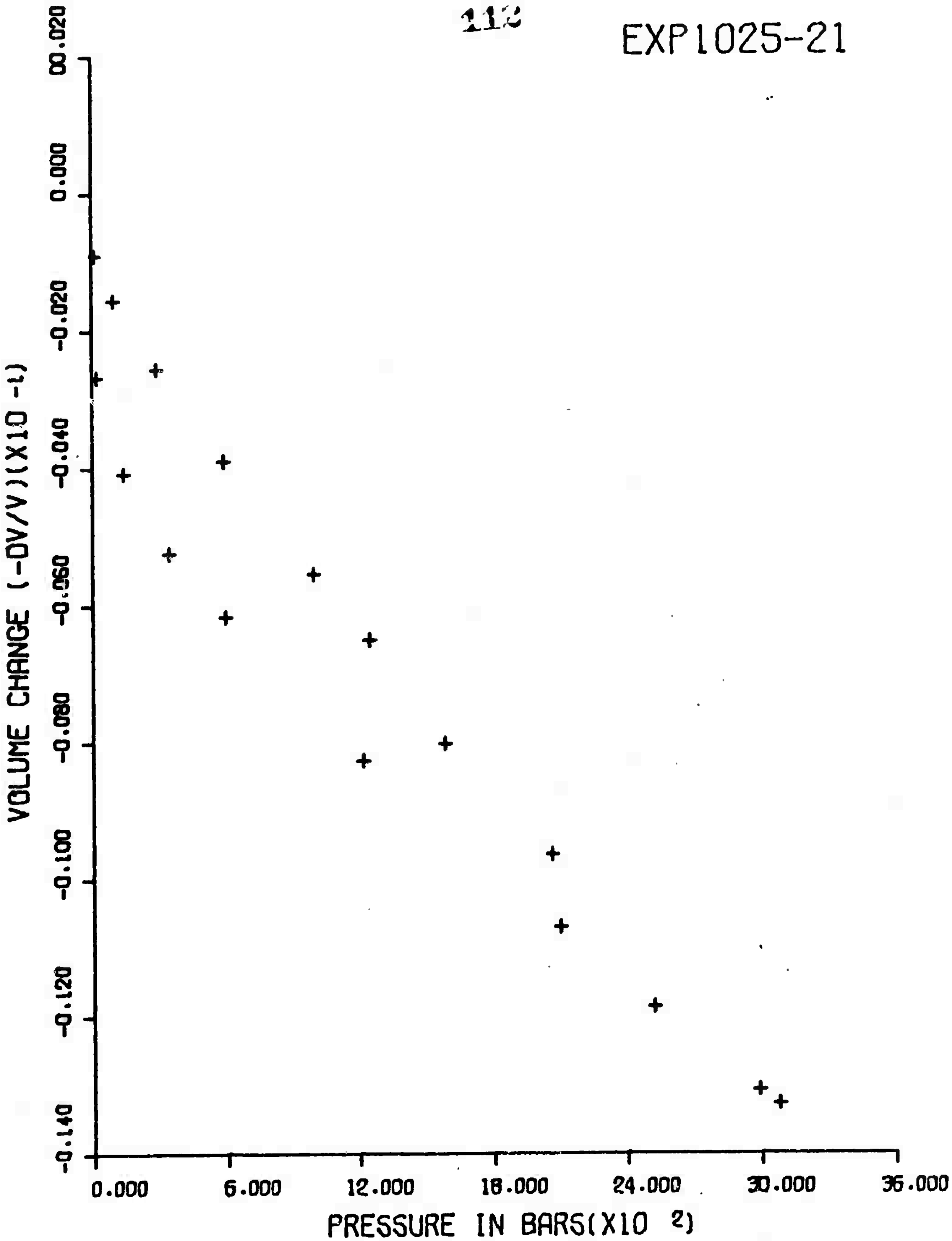
SHEAR VELOCITY - DRY BEREA SANDSTONE



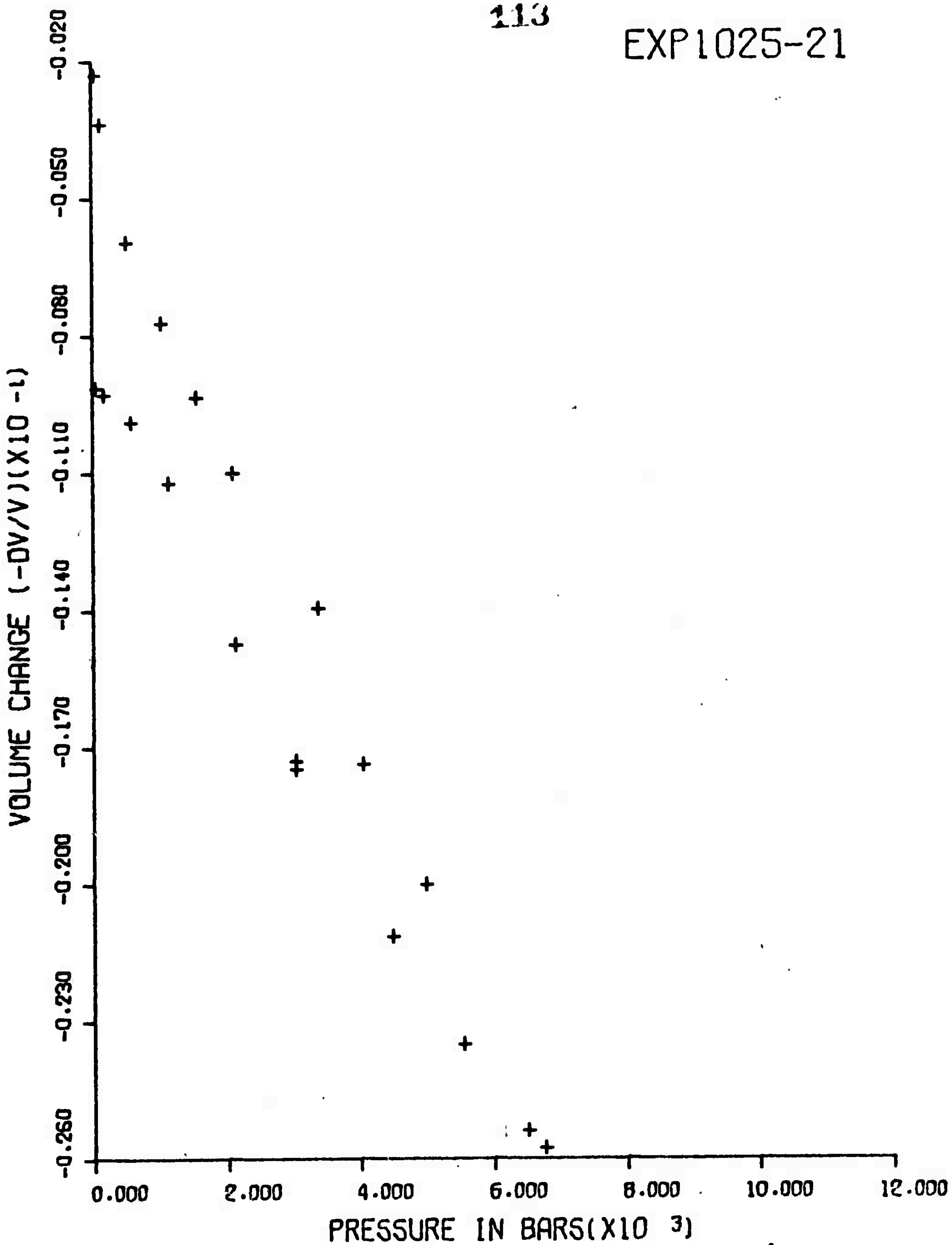
SHEAR VELOCITY-H2O FILLED BEREA SANDSTONE



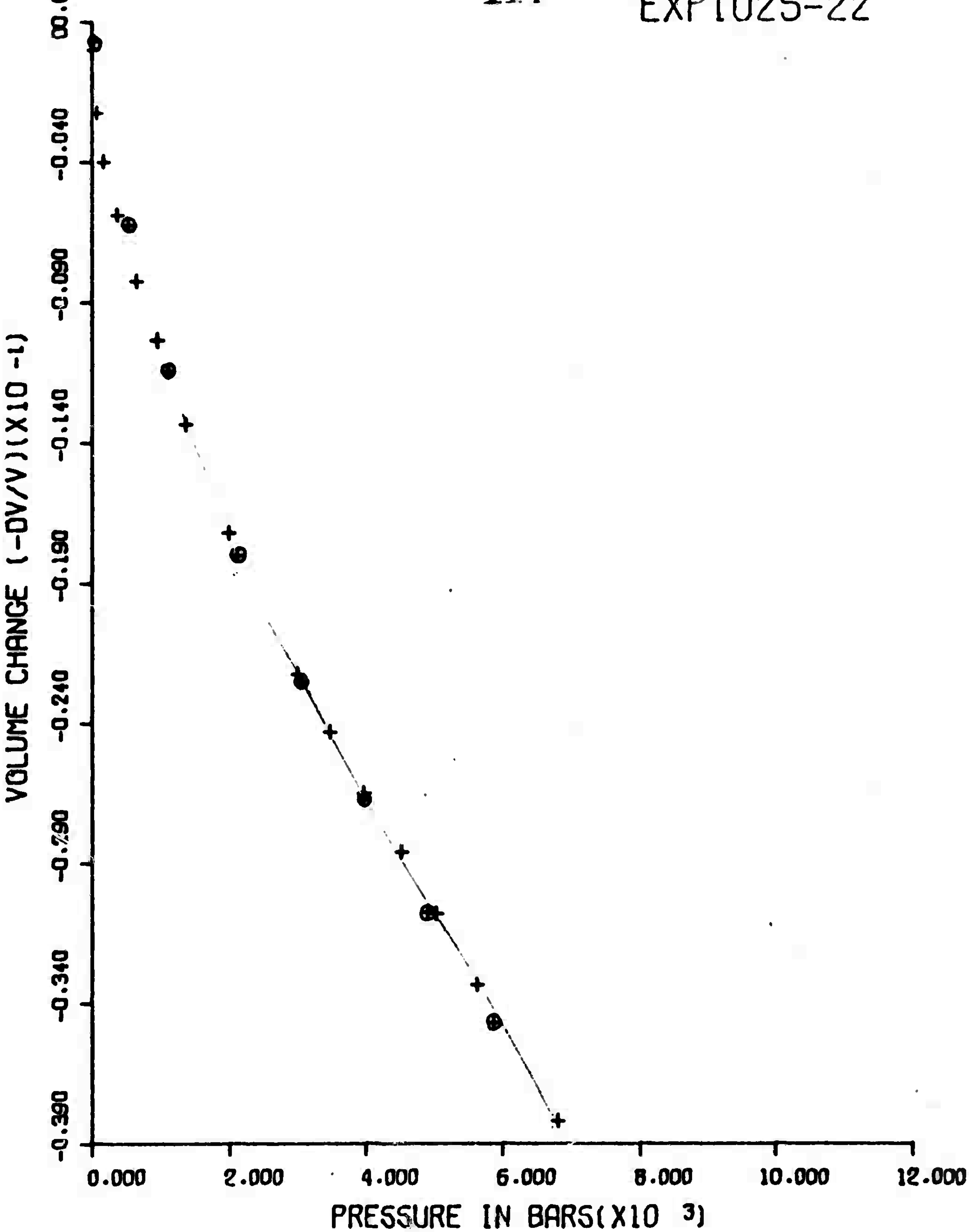
COMP VELOCITY-H2O FILLED SALEM LIMESTONE



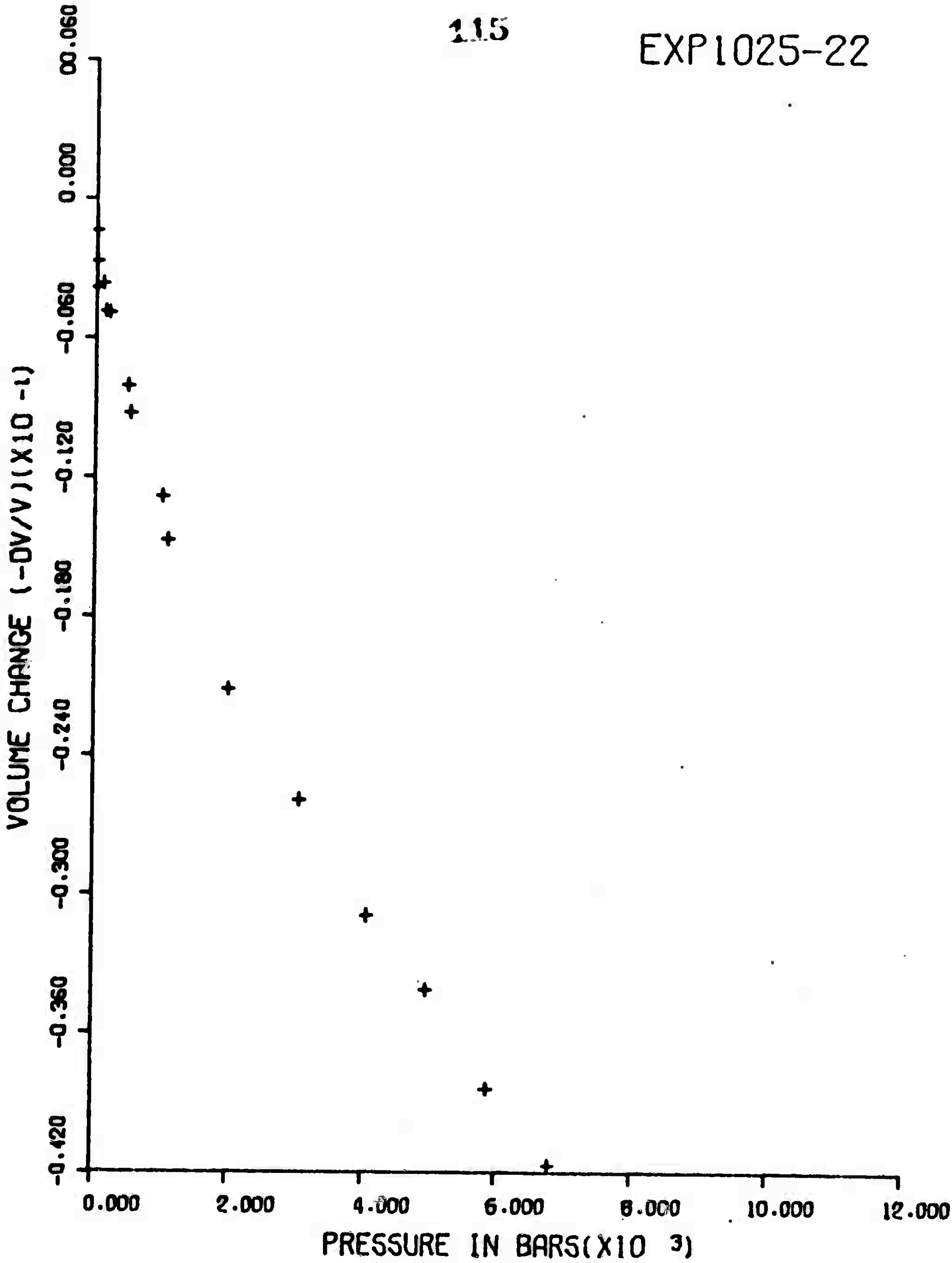
COMP VELOCITY-H2O FILLED SALEM LIMESTONE



COMP VELOCITY-H2O FILLED SALEM LIMESTONE

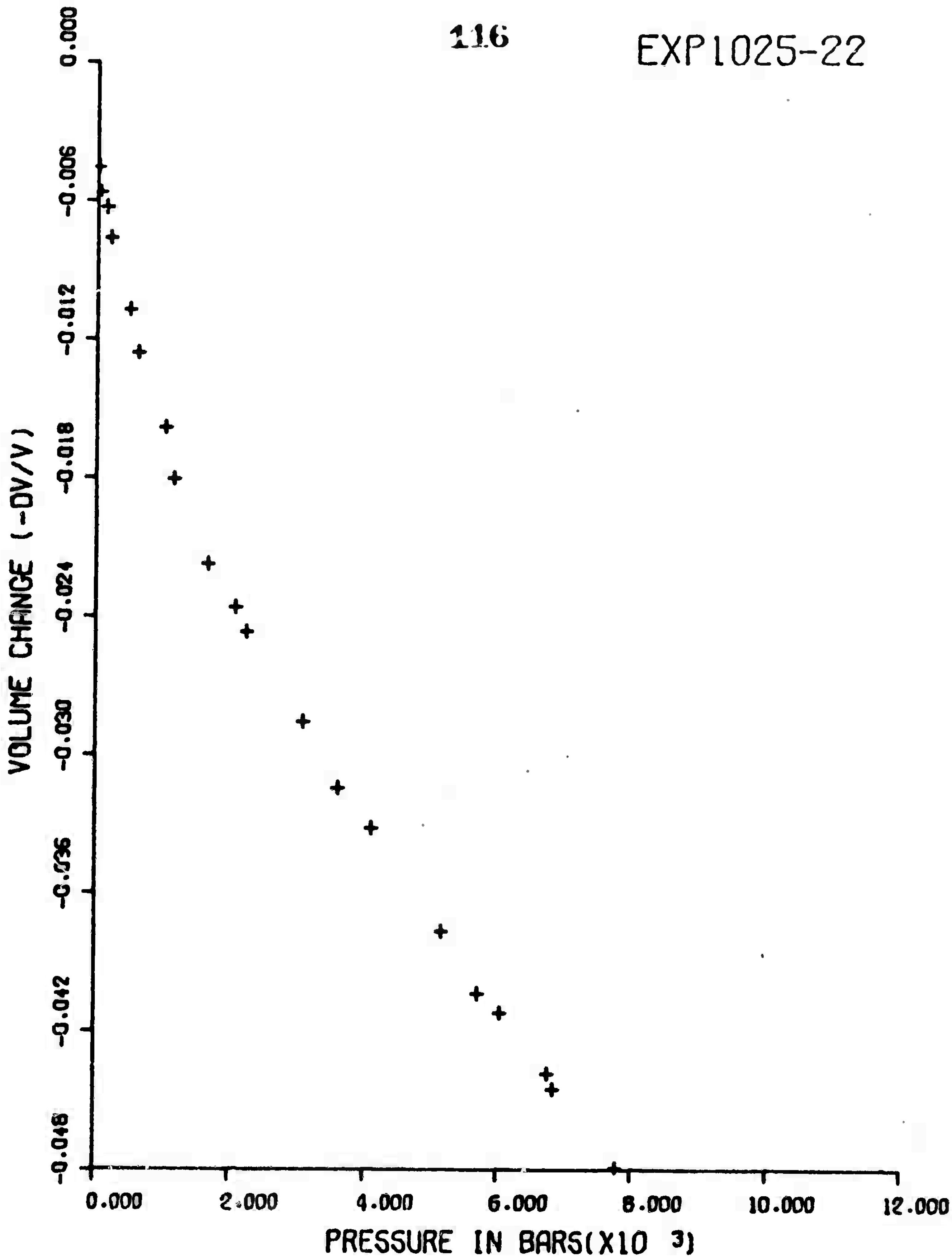


COMP VELOCITY-H2O FILLED BEREA SANDSTONE

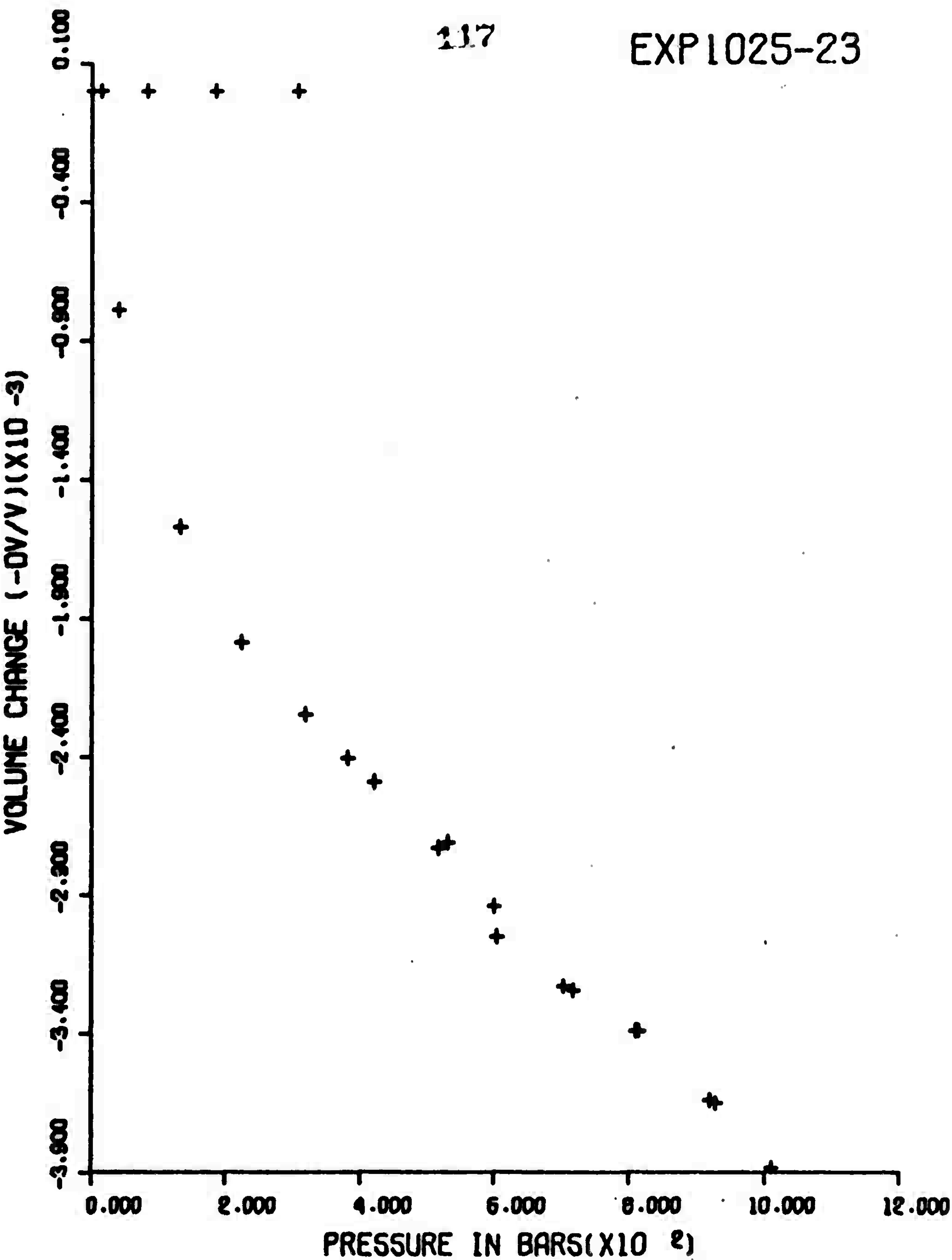


COMP VELOCITY-H2O FILLED BEREA SANDSTONE

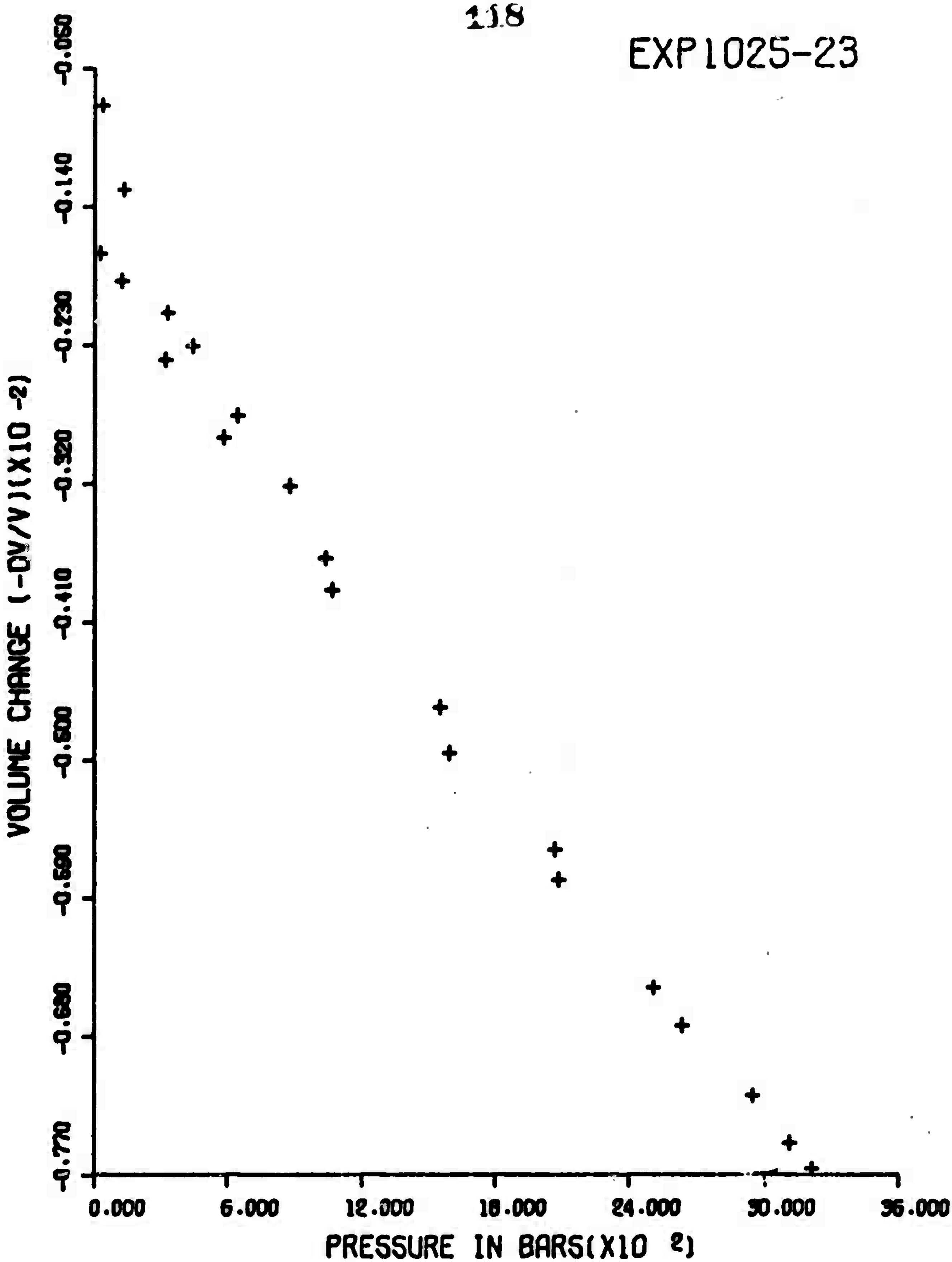
EXP1025-22



COMP VELOCITY-H2O FILLED BEREA SANDSTONE



COMPRESSIONAL VELOCITY WESTERLY GRANITE



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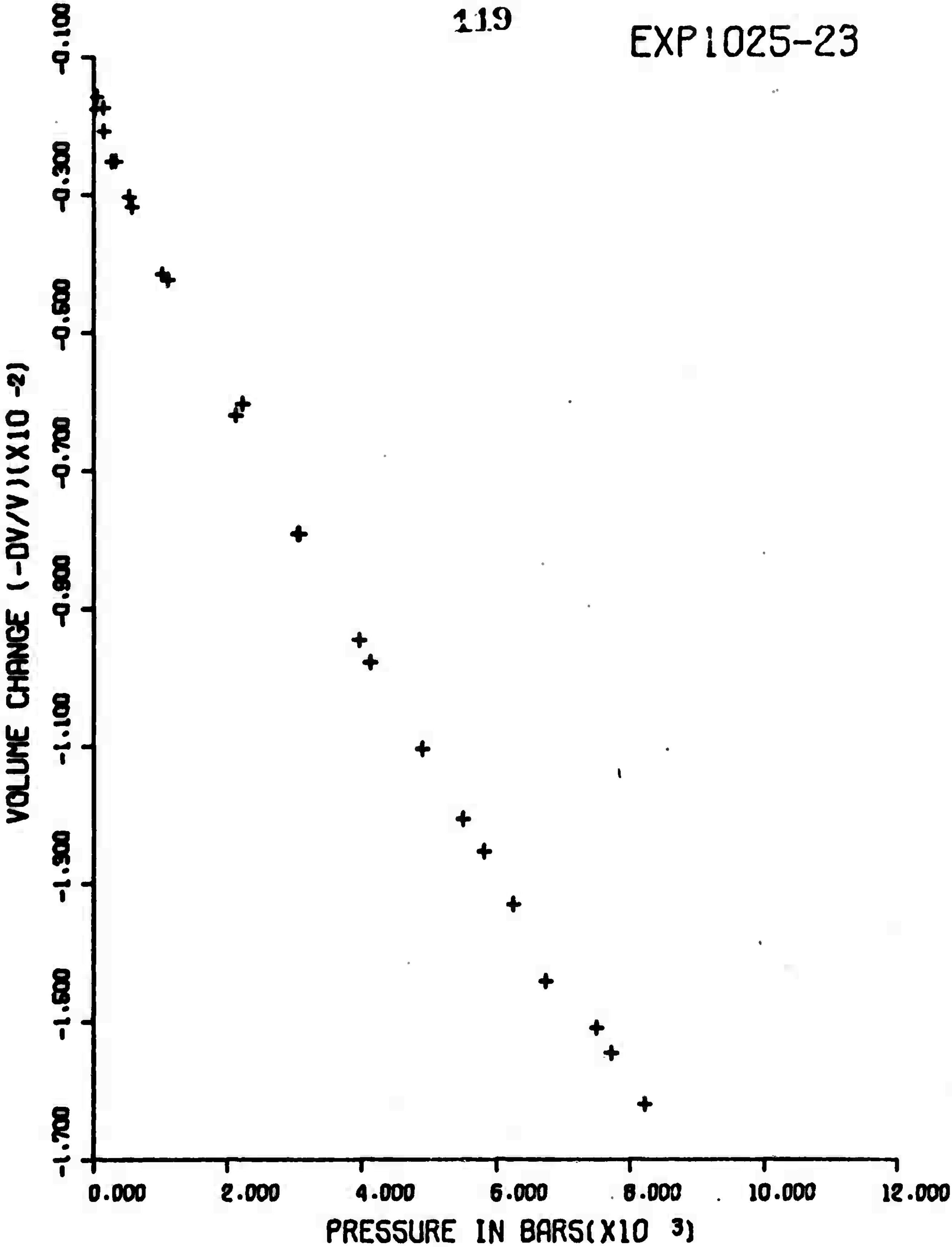
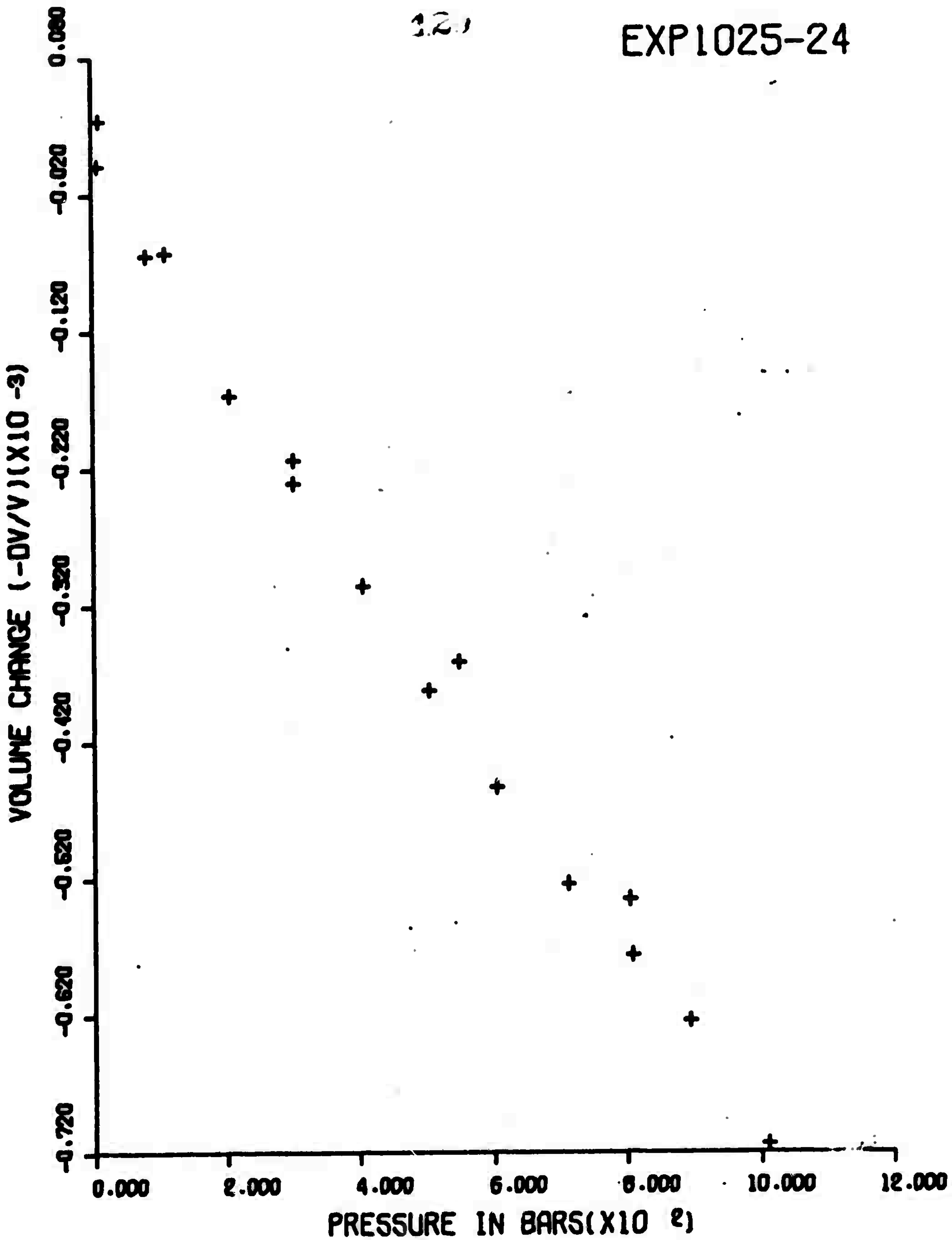
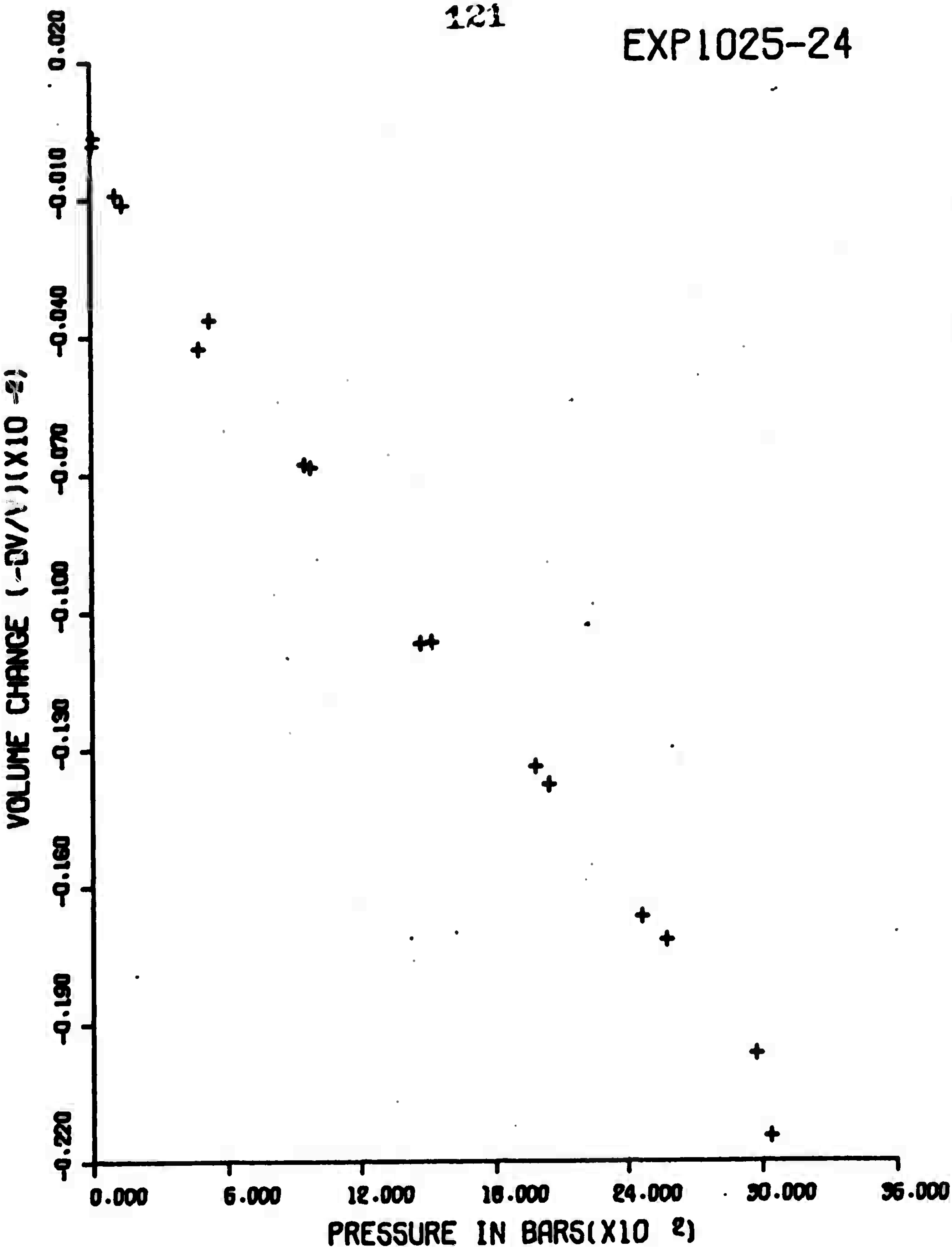


COMPRESSIONAL VELOCITY WESTERLY GRANITE

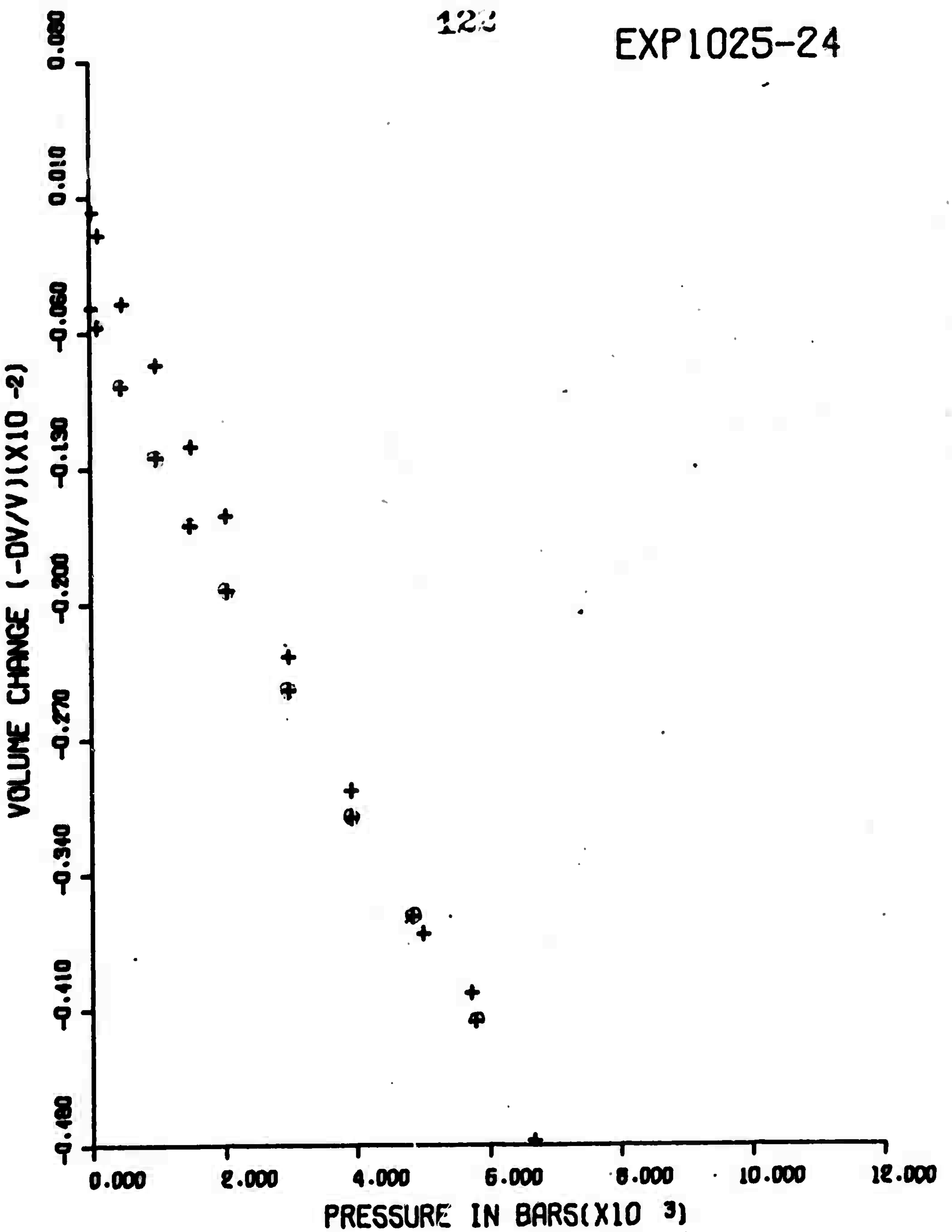


COMP VELOCITY H2O FILLED WESTER.Y GRANITE

EXP1025-24



COMP VELOCITY H2O FILLED WESTERLY GRANITE



COMP VELOCITY H2O FILLED WESTERLY GRANITE

APPENDIX III

```
                 PROGRAM DYNMOD (INPUT,OUTPUT)
000003           DIMENSION P(50), VP(50), VS(50), SV(50), PHI(50), VBULK(50),
                CVMEAN(50), POIS(50), BMOD(50), ALAME(50), SMOD(50), YMOD(50),
                CDEN(50), DTHETA(50), NAME(2), COND(6), CYCLE(6)
            CC  READ INPUT FOR SAMPLE, DO PROGRAM HOUSKEEPING
000003      1000 READ 2, (NAME)
000011           READ 7, (COND)
000017           READ 3, (OLEN,DIA,WGT,WGTH20,PORE,BARM)
            CC  CALCULATE VOLUME AND DENSITY
000037           VOL=(.7854*(DIA**2)*OLEN)/1000.
000043           DENO=WGT/VOL
000044           SVOLO=VOL/WGT
000046           WDEN=(WGT-WGTH20)/VOL
000050      1001 PRINT 4
000054           PRINT 5
000060           PRINT 2, (NAME)
000066           PRINT 7, (COND)
000074           READ 7, (CYCLE)
000102           PRINT 7, (CYCLE)
000110           PRINT 5
000114           PRINT 6,(OLEN,DENO,DIA,WDEN,WGT,SVOLO,WGTH20,PORE)
000140           PRINT 5
000144           PRINT 5
000150           PRINT 8
000154           PRINT 5
            CC  READ DATA AND CALCULATE
000160           READ 9,(NDATA)
000166           DO 100 I=1,NDATA
000170           READ 10,(P(I),VP(I),VS(I),SV(I))
000203           PHI(I)=VP(I)**2-1.333*VS(I)**2
000207           VBULK(I)=PHI(I)**0.5
000214           VMEAN(I)=1./((2./(3.*VS(I)**3)+1./(3.*VP(I)**3)))**0.3333
000227           POIS(I)=(VP(I)**2-2.*VS(I)**2)/(2.*(VP(I)**2-VS(I)**2))
000242           DEN(I)=1./SV(I)
000244           BMOD(I)=10.*DEN(I)*(VP(I)**2-1.333*VS(I)**2)
000252           SMOD(I)=10.*DEN(I)*VS(I)**2
000255           YMOD(I)=BMOD(I)*(3.-6.*POIS(I))
000262           ALAME(I)=10.*DEN(I)*(VP(I)**2-2.*VS(I)**2)
000270           PRINT 11,(P(I),VP(I),VS(I),DEN(I),BMOD(I),SMOD(I),YMOD(I),POIS(I),
                CALAME(I))
000315           DTHETA(I)=231.3*((DEN(I)/BARM)**0.333)*VMEAN(I)
000324       100 CONTINUE
000327           PRINT 4
000332           PRINT 5
000336           PRINT 12, (NAME)
000344           PRINT 7, (COND)
000352           PRINT 7, (CYCLE)
000360           PRINT 5
000364           PRINT 13
000370           PRINT 5
000374           PRINT 14,(P(I),SV(I),VMEAN(I),VBULK(I),PHI(I),DTHETA(I),I=1,NDATA)
000421           READ 15, (NI)
000427           IF (NI) 1000,1001,1002
000431      1002 CALL EXIT
```

```
000432         1 FORMAT (5X,2A10)
000432         2 FORMAT (5X,4A10)
000432         3 FORMAT (4F10.6,1A10,F5.2)
000432         4 FORMAT (1H1)
000432         5 FORMAT (/)
000432         6 FORMAT(10X,*LENGTH*,F9.3,1X,*MM*,10X,*DENSITY*,F11.4,1X,*GM/CC*,
                C/,10X,*DIAMETER*,F7.3,1X,*MM*,10X,*DEN W/O H2O*,F7.4,1X,*GM/CC*,
                C/,10X,*WEIGHT*,F9.3,1X,*GM*,10X,*SPEC VOL*,F10.4,1X,*CC/GM*,/,
                C10X,*WGT H2O*,F8.3,1X,*GM*,10X,*POROSITY *,3X,1A10)
000432         7 FORMAT (5X,6A10)
000432         8 FORMAT(4X,*PRESSURE*,3X,*VP*,6X,*VS*,4X,*DENSITY*,2X,*BULK*,3X,
                C*SHEAR*,3X,*YOUNGS*,1X,*POISSONS*,2X,*LAME*,/,36X,*MODULUS*,1X,
                C*MODULUS*,1X,*MODULUS*,2X,*RATIO*,2X,*CONSTANT*,/,7X,*KB*,4X,
                C*KM/SEC*,2X,*KM/SEC*,3X,*GM/CC*,4X,*KB*,6X,*KB*,6X,*KB*,14X,*KB*)
000432         9 FORMAT (I2)
000432        10 FORMAT (4F10.6)
000432        11 FORMAT(5X,3(F5.2,3X),F6.4,2X,3(F5.1,3X),F5.4,3X,F5.1)
000432        12 FORMAT (5X,4A10,*CONTINUED*)
000432        13 FORMAT(6X,*PRESSURE*,3X,*SPECIFIC*,5X,*MEAN*,7X,*BULK*,6X,*SEISMIC
                C*,5X,*DEBYE*,/,18X,*VOLUME*,4X,*VELOCITY*,3X,*VELOCITY*,3X,
                C*PARAMETER*,4X,*TEMP*,/,9X,*KB*,7X,*CC/GM*,6X,*KM/SEC*,5X,*KM/SEC*
                C,3X,11H(KM/SEC)**2,3X,*DEG K*)
000432        14 FORMAT(F12.2,F12.4,F10.2,F11.2,F11.2,F12.1)
000432        15 FORMAT (I2)
000432           END
```

*DRY BEREA SANDSTONE
FROM 1025-10 1025-11, VOL ABOVE 2KB EST FROM AXIAL STRAIN
0-1-0 KB PART OF 0-1-0-7.2-0 KB CYCLE

LENGTH	40.000 MM	DENSITY	2.1584 GM/CC
DIAMETER	25.270 MM	DEN W/O H2O	2.1584 GM/CC
WEIGHT	43.300 GM	SPEC VOL	0.4633 CC/GM
WGT H2O	0.000 GM	POROSITY	0.191

PRESSURE KB	VP KM/SEC	VS KM/SEC	DENSITY GM/CC	BULK MODULUS KB	SHEAR MODULUS KB	YOUNGS MODULUS KB	POISSONS RATIO	LAME CONSTANT KB
0.00	2.35	1.35	2.1584	66.8	39.3	98.7	.2[illegible]7	40.5
0.10	3.42	2.12	2.1636	123.4	97.2	231.1	.1880	58.6
0.20	3.67	2.36	2.1683	131.1	120.8	277.2	.1475	50.5
0.30	3.89	2.47	2.1711	152.0	132.5	308.0	.1622	63.6
0.40	3.96	2.54	2.1734	153.9	140.2	322.8	.1505	60.4
0.50	4.02	2.56	2.1758	161.5	142.6	330.6	.1589	66.4
0.60	4.05	2.57	2.1777	165.5	143.8	334.6	.1629	69.5
0.70	4.09	2.59	2.1796	169.7	146.2	340.8	.1653	72.2
0.80	4.11	2.61	2.1815	170.4	148.6	345.5	.1621	71.3
0.90	4.14	2.62	2.1829	174.4	149.8	349.5	.1660	74.5
1.00	4.17	2.63	2.1844	178.4	151.1	353.6	.1697	77.7
0.90	4.15	2.63	2.1825	174.6	151.0	351.7	.1644	74.0
0.80	4.14	2.62	2.1815	174.3	149.7	349.3	.1660	74.4
0.70	4.10	2.59	2.1796	171.5	146.2	341.6	.1680	74.0
0.60	4.06	2.57	2.1777	167.2	143.8	335.4	.1657	71.3
0.50	4.01	2.55	2.1758	161.3	141.5	328.5	.1605	66.9
0.40	3.96	2.52	2.1739	156.9	138.1	320.3	.1597	64.8
0.30	3.90	2.48	2.1720	152.3	133.6	310.2	.1606	63.2
0.20	3.76	2.36	2.1701	145.7	120.9	284.1	.1750	65.1
0.10	3.46	2.12	2.1678	129.6	97.4	233.8	.1995	64.7
0.00	2.40	1.34	2.1626	72.8	38.8	98.9	.2735	46.9

*DRY BEREA SANDSTONE
FROM 1025-10 1025-11, VOL ABOVE 2KB EST FROM AXIAL STRAIN
0-1-0 KB PART OF 0-1-0-7.2-0 KB CYCLE

PRESSURE KB	SPECIFIC VOLUME CC/GM	MEAN VELOCITY KM/SEC	BULK VELOCITY KM/SEC	SEISMIC PARAMETER (KM/SEC)**2	DEBYE TEMP DEG K
0.00	0.4633	1.50	1.76	3.09	165.2
0.10	0.4622	2.34	2.39	5.71	257.7
0.20	0.4612	2.59	2.46	6.04	285.8
0.30	0.4606	2.72	2.65	7.00	299.7
0.40	0.4601	2.79	2.66	7.08	308.0
0.50	0.4596	2.81	2.72	7.42	310.8
0.60	0.4592	2.83	2.76	7.60	312.2
0.70	0.4588	2.85	2.79	7.79	314.8
0.80	0.4584	2.87	2.79	7.81	317.2
0.90	0.4581	2.88	2.83	7.99	318.6
1.00	0.4578	2.89	2.86	8.17	320.0
0.90	0.4582	2.89	2.83	8.00	319.8
0.80	0.4584	2.88	2.83	7.99	318.6
0.70	0.4588	2.85	2.81	7.87	314.9
0.60	0.4592	2.83	2.77	7.68	312.3
0.50	0.4596	2.80	2.72	7.41	309.6
0.40	0.4600	2.77	2.69	7.22	305.9
0.30	0.4604	2.73	2.65	7.01	300.9
0.20	0.4608	2.60	2.59	6.71	286.7
0.10	0.4613	2.34	2.45	5.98	258.1
0.00	0.4624	1.49	1.83	3.37	164.4

*DRY BEREA SANDSTONE
FROM 1025-10 1025-11, VOL ABOVE 2KB EST FROM AXIAL STRAIN
0-7.2-0 KB PART OF 0-1-0-7.2-0 KB CYCLE

LENGTH	40.000 MM	DENSITY	2.1584 GM/CC
DIAMETER	25.270 MM	DEN W/O H2O	2.1584 GM/CC
WEIGHT	43.300 GM	SPEC VOL	0.4633 CC/GM
WGT H2O	0.000 GM	POROSITY	0.191

PRESSURE KB	VP KM/SEC	VS KM/SEC	DENSITY GM/CC	BULK MODULUS KB	SHEAR MODULUS KB	YOUNGS MODULUS KB	POISSONS RATIO	LAME CONSTANT KB
0.00	2.40	1.34	2.1626	72.8	38.8	98.9	.2735	46.9
0.20	3.76	2.36	2.1701	145.7	120.9	284.1	.1750	65.1
0.40	3.96	2.52	2.1739	156.9	138.1	320.3	.1597	64.8
0.60	4.06	2.57	2.1313	163.7	140.8	328.3	.1657	69.8
1.00	4.14	2.62	2.1844	174.5	149.9	349.8	.1660	74.5
1.50	4.18	2.63	2.1896	180.7	151.5	355.2	.1724	79.7
2.00	4.20	2.63	2.1939	184.7	151.8	357.5	.1775	83.5
2.50	4.22	2.60	2.1988	193.4	148.6	355.1	.1941	94.3
3.00	4.24	2.59	2.2036	199.1	147.8	355.6	.2024	100.5
3.50	4.26	2.61	2.2080	200.2	150.4	360.9	.1995	99.9
4.00	4.28	2.60	2.2124	205.9	149.6	361.3	.2076	106.2
4.50	4.25	2.57	2.2178	205.3	146.5	355.1	.2118	107.6
5.00	4.21	2.48	2.2548	214.8	138.7	342.4	.2343	122.3
5.50	4.16	2.44	2.2878	214.4	136.2	337.3	.2378	123.5
6.00	4.17	2.48	2.3105	212.3	142.1	348.6	.2264	117.6
6.50	4.26	2.55	2.3375	221.6	152.0	371.2	.2208	120.2
7.00	4.32	2.58	2.3524	230.3	156.6	383.0	.2228	125.8
7.20	4.34	2.59	2.3574	233.2	158.1	387.0	.2234	127.8
6.00	4.16	2.45	2.3419	217.9	140.6	347.1	.2345	124.1
5.00	4.00	2.34	2.3277	202.5	127.5	316.1	.2399	117.5
4.00	3.78	2.22	2.3132	178.6	114.0	282.0	.2367	102.5
3.00	3.50	2.05	2.2936	152.5	96.4	238.9	.2389	88.2
2.00	3.07	1.78	2.2691	118.0	71.9	179.3	.2468	70.1

*DRY BEREA SANDSTONE
FROM 1025-10 1025-11, VOL ABOVE 2KB EST FROM AXIAL STRAIN
0-7.2-0 KB PART OF 0-1-0-7.2-0 KB CYCLE

PRESSURE KB	SPECIFIC VOLUME CC/GM	MEAN VELOCITY KM/SEC	BULK VELOCITY KM/SEC	SEISMIC PARAMETER (KM/SEC)**2	DEBYE TEMP DEG K
0.00	0.4624	1.49	1.83	3.37	164.4
0.20	0.4608	2.60	2.59	6.71	286.7
0.40	0.4600	2.77	2.69	7.22	305.9
0.60	0.4692	2.83	2.77	7.68	310.1
1.00	0.4578	2.88	2.83	7.99	318.7
1.50	0.4567	2.89	2.87	8.29	320.4
2.00	0.4558	2.90	2.90	8.47	320.8
2.50	0.4548	2.87	2.97	8.80	317.9
3.00	0.4538	2.86	3.01	9.04	317.2
3.50	0.4529	2.88	3.01	9.07	319.7
4.00	0.4520	2.87	3.05	9.31	319.0
4.50	0.4509	2.84	3.04	9.26	315.7
5.00	0.4435	2.75	3.09	9.53	307.1
5.50	0.4371	2.70	3.06	9.37	303.8
6.00	0.4328	2.75	3.03	9.19	309.4
6.50	0.4278	2.82	3.08	9.48	319.1
7.00	0.4251	2.86	3.13	9.79	323.6
7.20	0.4242	2.87	3.15	9.89	325.1
6.00	0.4270	2.71	3.05	9.30	307.3
5.00	0.4296	2.59	2.95	8.70	293.1
4.00	0.4323	2.46	2.78	7.72	277.4
3.00	0.4360	2.27	2.58	6.65	255.5
2.00	0.4407	1.98	2.28	5.20	221.2

WATER FILLED BEREA SANDSTONE
FROM 1025-14, 1025-22, 1025-25, VP CYCLED SEVERAL TIMES
0-6.6-0 KB PART OF 0-6.6-0 KB CYCLE

LENGTH	40.000 MM	DENSITY	2.3239 GM/CC
DIAMETER	25.298 MM	DEN W/O H2O	2.1523 GM/CC
WEIGHT	46.724 GM	SPEC VOL	0.4303 CC/GM
WGT H2O	3.450 GM	POROSITY	0.191

PRESSURE KB	VP KM/SEC	VS KM/SEC	DENSITY GM/CC	BULK MODULUS KB	SHEAR MODULUS KB	YOUNGS MODULUS KB	POISSONS RATIO	LAME CONSTANT KB
0.00	3.35	2.11	2.3239	122.9	103.5	242.4	.1712	53.9
0.10	3.70	2.20	2.3306	168.7	112.8	276.8	.2266	93.5
0.20	3.91	2.27	2.3321	196.3	120.2	299.5	.2458	116.2
0.30	4.01	2.34	2.3364	205.2	127.9	317.8	.2418	119.8
0.40	4.09	2.40	2.3388	211.7	134.7	333.5	.2374	121.8
0.50	4.15	2.46	2.3411	214.3	141.7	348.3	.2291	119.8
0.60	4.21	2.51	2.3426	218.5	147.6	361.4	.2243	120.0
0.70	4.22	2.52	2.3445	219.1	148.9	364.2	.2229	119.7
0.80	4.23	2.53	2.3468	219.7	150.2	367.1	.2215	119.5
0.90	4.24	2.53	2.3479	221.0	150.9	368.8	.2218	120.3
1.00	4.24	2.54	2.3495	220.3	151.6	370.0	.2201	119.2
1.50	4.26	2.56	2.3573	221.9	154.5	376.2	.2174	118.8
2.00	4.30	2.58	2.3645	227.4	157.4	383.7	.2188	122.4
3.00	4.40	2.61	2.3767	244.3	161.9	397.9	.2286	136.3
4.00	4.46	2.62	2.3871	256.4	163.9	405.3	.2365	147.1
4.50	4.36	2.62	2.3918	235.8	164.2	399.8	.2174	126.3
5.00	4.36	2.55	2.3966	247.9	155.8	386.6	.2400	143.9
5.50	4.39	2.46	2.4018	269.1	145.3	369.6	.2711	172.2
6.00	4.45	2.46	2.4073	282.5	145.7	373.0	.2800	185.3
6.60	4.56	2.50	2.4155	301.0	151.0	388.1	.2851	200.3
6.00	4.56	2.49	2.4079	301.7	149.3	384.5	.2876	202.1
5.00	4.40	2.46	2.3984	270.9	145.1	369.5	.2726	174.0
4.00	4.28	2.41	2.3883	252.6	138.7	351.8	.2679	160.1
3.00	4.19	2.35	2.3773	242.4	131.3	333.7	.2705	15[illegible].8
2.00	4.08	2.24	2.3645	235.5	118.6	304.8	.2843	156.3
1.00	3.94	2.12	2.3488	223.9	105.6	273.7	.2962	153.5
0.50	3.77	2.06	2.3384	200.7	98.7	254.5	.2886	134.8
0.15	3.57	2.00	2.3288	172.6	93.2	236.9	.2713	110.5

WATER FILLED BEREA SANDSTONE CONTINUED
FROM 1025-14, 1025-22, 1025-25, VP CYCLED SEVERAL TIMES
0-6.6-0 KB PART OF 0-6.6-0 KB CYCLE

PRESSURE KB	SPECIFIC VOLUME CC/GM	MEAN VELOCITY KM/SEC	BULK VELOCITY KM/SEC	SEISMIC PARAMETER (KM/SEC)**2	DEBYE TEMP DEG K
0.00	0.4303	2.32	2.30	5.29	262.2
0.10	0.4291	2.44	2.69	7.24	275.2
0.20	0.4288	2.52	2.90	8.42	284.7
0.30	0.4280	2.60	2.96	8.78	293.5
0.40	0.4276	2.66	3.01	9.05	301.0
0.50	0.4271	2.72	3.03	9.16	308.3
0.60	0.4269	2.78	3.05	9.33	314.5
0.70	0.4265	2.79	3.06	9.34	315.8
0.80	0.4261	2.80	3.06	9.36	317.1
0.90	0.4259	2.81	3.07	9.41	317.7
1.00	0.4256	2.81	3.06	9.38	318.4
1.50	0.4242	2.83	3.07	9.41	321.2
2.00	0.4229	2.85	3.10	9.62	324.0
3.00	0.4207	2.89	3.21	10.28	328.7
4.00	0.4189	2.90	3.28	10.74	330.8
4.50	0.4181	2.90	3.14	9.86	330.3
5.00	0.4172	2.83	3.22	10.34	322.5
5.50	0.4163	2.74	3.35	11.21	312.5
6.00	0.4154	2.74	3.43	11.74	313.1
6.60	0.4140	2.79	3.53	12.46	318.7
6.00	0.4153	2.78	3.54	12.53	317.2
5.00	0.4169	2.74	3.36	11.29	312.4
4.00	0.4187	2.68	3.25	10.58	305.4
3.00	0.4207	2.62	3.19	10.19	297.5
2.00	0.4229	2.50	3.16	9.96	283.5
1.00	0.4258	2.37	3.09	9.53	268.1
0.50	0.4276	2.29	2.93	8.58	259.3
0.15	0.4294	2.23	2.72	7.41	251.5

DRY SALEM LIMESTONE
FROM 1025-4, 1025-9, 1025-1[illegible], VS 5-0-5 KB ESTIMATED
0-1-0 KB PART OF 0-1-0-5-0-7-0 KB CYCLE

LENGTH	38.250 MM	DENSITY	2.3540 GM/CC
DIAMETER	25.300 MM	DEN W/O H2O	2.3540 GM/CC
WEIGHT	45.266 GM	SPEC VOL	0.4248 CC/GM
WGT H2O	0.000 GM	POROSITY	0.125

PRESSURE KB	VP KM/SEC	VS KM/SEC	DENSITY GM/CC	BULK MODULUS KB	SHEAR MODULUS KB	YOUNGS MODULUS KB	POISSONS RATIO	LAME CONSTANT KB
0.00	3.57	2.68	2.3540	74.6	169.1	289.1	*.146	-38.1
0.10	3.93	2.69	2.3552	136.6	170.4	361.2	.0592	22.9
0.20	4.21	2.70	2.3563	188.7	171.8	395.4	.1507	74.1
0.30	4.44	2.70	2.3573	235.6	171.8	414.8	.2066	121.0
0.40	4.62	2.72	2.3582	270.8	174.5	430.9	.2347	154.4
0.50	4.66	2.72	2.3591	279.6	174.5	433.5	.2416	163.2
0.60	4.68	2.72	2.3601	284.2	174.6	434.9	.2450	167.7
0.70	4.69	2.72	2.3611	286.5	174.7	435.6	.2466	170.0
0.80	4.72	2.72	2.3622	293.3	174.8	437.5	.2514	176.7
0.90	4.79	2.72	2.3633	309.2	174.8	441.4	.2620	192.5
1.00	4.92	2.73	2.3643	337.4	176.2	450.3	.2776	219.9
0.90	4.91	2.72	2.3633	336.7	174.8	447.2	.2786	220.1
0.80	4.90	2.71	2.3627	336.0	173.5	444.2	.2797	220.2
0.60	4.87	2.70	2.3611	330.5	172.1	440.1	.2781	215.7
0.40	4.81	2.68	2.3593	320.0	169.5	432.2	.2749	206.9
0.20	4.61	2.66	2.3573	278.6	166.8	417.2	.2504	167.4
0.10	4.41	2.65	2.3562	237.7	165.5	403.0	.2174	127.3
0.00	3.86	2.64	2.3550	132.1	164.1	348.3	.0606	22.6

DRY SALEM LIMESTONE CONTINUED
FROM 1025-4, 1025-9, 1025-13, VS 5-0-5 KB ESTIMATED
0-1-0 KB PART OF 0-1-0-5-0-7-0 KB CYCLE

PRESSURE KB	SPECIFIC VOLUME CC/GM	MEAN VELOCITY KM/SEC	BULK VELOCITY KM/SEC	SEISMIC PARAMETER (KM/SEC)**2	DEBYE TEMP DEG K
0.00	0.4248	2.88	1.78	3.17	326.0
0.10	0.4246	2.93	2.41	5.80	332.0
0.20	0.4244	2.97	2.83	8.01	336.0
0.30	0.4242	2.98	3.16	10.00	338.0
0.40	0.4240	3.01	3.39	11.48	341.6
0.50	0.4239	3.02	3.44	11.85	342.0
0.60	0.4237	3.02	3.47	12.04	342.1
0.70	0.4235	3.02	3.48	12.13	342.3
0.80	0.4233	3.02	3.52	12.42	342.5
0.90	0.4231	3.02	3.62	13.08	343.0
1.00	0.4230	3.04	3.78	14.27	344.9
0.90	0.4231	3.03	3.77	14.25	343.7
0.80	0.4232	3.02	3.77	14.22	342.4
0.60	0.4235	3.01	3.74	14.00	341.0
0.40	0.4238	2.98	3.68	13.56	338.3
0.20	0.4242	2.95	3.44	11.82	334.7
0.10	0.4244	2.93	3.18	10.09	332.1
0.00	0.4246	2.88	2.37	5.61	325.8

DRY SALEM LIMESTONE
FROM 1025-4, 1025-9, 1025-13, VS 5-0-5 KB ESTIMATED
0-5-0 KB PART OF 0-1-0-5-0-7-0 KB CYCLE

LENGTH	38.250 MM	DENSITY	2.3540 GM/CC
DIAMETER	25.300 MM	DEN W/O H2O	2.3540 GM/CC
WEIGHT	45.266 GM	SPEC VOL	0.4248 CC/GM
WGT H2O	0.000 GM	POROSITY	0.125

PRESSURE KB	VP KM/SEC	VS KM/SEC	DENSITY GM/CC	BULK MODULUS KB	SHEAR MODULUS KB	YOUNGS MODULUS KB	POISSONS RATIO	LAME CONSTANT KB
0.00	3.86	2.64	2.3550	132.1	164.1	348.3	.0606	22.6
0.20	4.62	2.66	2.3574	280.8	166.8	417.8	.2521	169.6
0.40	4.76	2.68	2.3596	308.7	169.5	429.8	.2679	195.7
0.60	4.85	2.70	2.3618	326.0	172.2	439.3	.2755	211.2
0.80	4.90	2.71	2.3629	336.0	173.5	444.2	.2797	220.3
1.00	4.92	2.72	2.3646	339.2	174.9	447.9	.2799	222.5
1.50	4.95	2.72	2.3708	347.1	175.4	450.4	.2837	230.1
2.00	4.97	2.73	2.3838	352.0	177.7	456.3	.2839	233.5
2.50	5.20	2.71	2.4048	414.8	176.6	464.1	.3136	297.0
3.00	5.11	2.81	2.4282	378.5	191.7	492.2	.2833	250.6
4.00	5.31	2.70	2.4714	456.7	180.2	477.7	.3256	336.5
5.00	5.36	2.88	2.5022	442.2	207.5	538.5	.2971	303.8
4.00	5.32	2.88	2.4961	430.5	207.0	535.4	.2927	292.4
3.00	5.27	2.84	2.4897	423.8	200.8	520.3	.2954	289.8
2.00	5.13	2.71	2.4804	409.9	182.2	476.0	.3065	288.4
1.00	4.75	2.42	2.4709	364.6	144.7	383.4	.3247	268.1
0.50	4.38	2.14	2.4614	321.9	112.7	302.9	.3432	246.8
0.00	3.32	1.77	2.4414	167.1	76.5	199.1	.3015	116.1

DRY SALEM LIMESTONE   CONTINUED
FROM 1025-4, 1025-9, 1025-13, VS 5-0-5 KB ESTIMATED
0-5-0 KB PART OF 0-1-0-5-0-7-0 KB CYCLE

PRESSURE KB	SPECIFIC VOLUME CC/GM	MEAN VELOCITY KM/SEC	BULK VELOCITY KM/SEC	SEISMIC PARAMETER (KM/SEC)**2	DEBYE TEMP DEG K
0.00	0.4246	2.88	2.37	5.61	325.8
0.20	0.4242	2.95	3.45	11.91	334.7
0.40	0.4238	2.98	3.62	13.08	338.0
0.60	0.4234	3.01	3.72	13.80	340.9
0.80	0.4232	3.02	3.77	14.22	342.4
1.00	0.4229	3.03	3.79	14.34	343.8
1.50	0.4218	3.03	3.83	14.64	344.3
2.00	0.4195	3.04	3.84	14.77	346.2
2.50	0.4158	3.03	4.15	17.25	345.9
3.00	0.4118	3.13	3.95	15.59	358.5
4.00	0.4046	3.03	4.30	18.48	348.3
5.00	0.3996	3.22	4.20	17.67	371.7
4.00	0.4006	3.21	4.15	17.25	371.2
3.00	0.4017	3.17	4.13	17.02	365.9
2.00	0.4032	3.03	4.07	16.53	349.2
1.00	0.4047	2.71	3.84	14.76	312.2
0.50	0.4063	2.40	3.62	13.08	276.4
0.00	0.4096	1.98	2.62	6.85	226.7

DRY SALEM LIMESTONE
FROM 1025-4, 1025-9, 1025-13, VS 5-0-5 KB ESTIMATED
0-7-0 KB PART OF 0-1-0-5-0-7-0 KB CYCLE

LENGTH	38.250 MM		DENSITY	2.3540 GM/CC
DIAMETER	25.300 MM		DEN W/O H2O	2.3540 GM/CC
WEIGHT	45.266 GM		SPEC VOL	0.4248 CC/GM
WGT H2O	0.000 GM		POROSITY	0.125

PRESSURE KB	VP KM/SEC	VS KM/SEC	DENSITY GM/CC	BULK MODULUS KB	SHEAR MODULUS KB	YOUNGS MODULUS KB	POISSONS RATIO	LAME CONSTANT KB
0.00	3.32	1.77	2.4414	167.1	76.5	199.1	.3015	116.1
0.50	4.24	2.14	2.4557	291.6	112.5	299.0	.3291	216.6
1.00	4.62	2.42	2.4640	333.6	144.3	378.4	.3109	237.3
2.00	5.02	2.71	2.4763	381.6	181.9	470.9	.2944	260.3
3.00	5.20	2.82	2.4863	408.7	197.7	510.9	.2917	276.9
4.00	5.40	2.87	2.4946	453.5	205.5	535.6	.3032	316.5
4.50	5.39	2.90	2.4989	445.8	210.2	544.9	.2963	305.7
5.00	5.32	3.00	2.5031	408.1	225.3	570.9	.2669	257.9
6.00	5.40	2.97	2.5119	437.1	221.6	568.7	.2832	289.3
7.00	5.45	3.00	2.5202	446.2	226.8	581.9	.2826	294.9
6.00	5.45	3.00	2.5146	445.2	226.3	580.7	.2826	294.3
5.00	5.42	3.00	2.5099	436.2	225.9	578.0	.2792	285.5
4.00	5.35	3.00	2.5037	416.3	225.3	572.8	.2707	266.0
3.00	5.22	2.97	2.4969	386.8	220.2	555.4	.2607	239.9
2.00	5.03	2.90	2.4900	350.8	209.4	524.1	.2510	211.2
1.00	4.63	2.66	2.4807	297.8	175.5	440.2	.2537	180.7
0.50	4.22	2.40	2.4720	250.4	142.4	359.2	.2610	155.4
0.00	3.20	1.77	2.4510	148.6	76.8	196.5	.2796	97.4

DRY SALEM LIMESTONE CONTINUED
FROM 1025-4, 1025-9, 1025-13, VS 5-0-5 KB ESTIMATED
0-7-0 KB PART OF 0-1-0-5-0-7-0 KB CYCLE

PRESSURE KB	SPECIFIC VOLUME CC/GM	MEAN VELOCITY KM/SEC	BULK VELOCITY KM/SEC	SEISMIC PARAMETER (KM/SEC)**2	DEBYE TEMP DEG K
0.00	0.4096	1.98	2.62	6.85	226.7
0.50	0.4072	2.40	3.45	11.87	275.6
1.00	0.4058	2.71	3.68	13.54	311.3
2.00	0.4038	3.02	3.93	15.41	348.5
3.00	0.4022	3.15	4.05	16.44	363.0
4.00	0.4009	3.21	4.26	18.18	370.3
4.50	0.4002	3.24	4.22	17.84	374.1
5.00	0.3995	3.34	4.04	16.31	385.8
6.00	0.3981	3.31	4.17	17.40	383.2
7.00	0.3968	3.34	4.21	17.71	387.4
6.00	0.3977	3.34	4.21	17.71	387.2
5.00	0.3984	3.34	4.17	17.38	386.7
4.00	0.3994	3.34	4.08	16.63	386.0
3.00	0.4005	3.30	3.94	15.49	381.4
2.00	0.4016	3.22	3.75	14.09	371.6
1.00	0.4031	2.95	3.46	12.01	340.5
0.50	0.4045	2.67	3.18	10.13	307.2
0.00	0.4080	1.97	2.46	6.06	226.4

APPENDIX IV

COMPRESSIBILITY OF SALEM LIMESTONE TO 16KB DRY

TEMPERATURE = 23.3 NDATA = 47 EXPERIMENT NO. 18 PAGE

PRESSURE IN BARS	VOL CC/GM
0.	0.42577
400.	0.42575
800.	0.42455
1200.	0.42337
1600.	0.42225
2000.	0.42092
2399.	0.41890
2799.	0.41659
3198.	0.41452
3598.	0.41479
3997.	0.40754
4396.	0.40461
4795.	0.40256
5193.	0.39939
5592.	0.39499
6389.	0.39258
7186.	0.38832
7982.	0.38656
8778.	0.38120
9573.	0.37907
10368.	0.37716
11162.	0.37479
11956.	0.37214
12749.	0.37023
13542.	0.36833
14335.	0.36677
15127.	0.36543
14335.	0.36639
13542.	0.36676
12749.	0.36736
11956.	0.36768
11162.	0.36827
10368.	0.36882
9573.	0.36930
8778.	0.37015
7982.	0.37069
7186.	0.37132
6389.	0.37193
5592.	0.37279
4795.	0.37357
3997.	0.37441
3198.	0.37513

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COMPRESSIBILITY OF SALEM LIMESTONE TO 16KB DRY

TEMPERATURE = 23.30 NDATA = 17 EXPERIMENT NO. 18 PAGE

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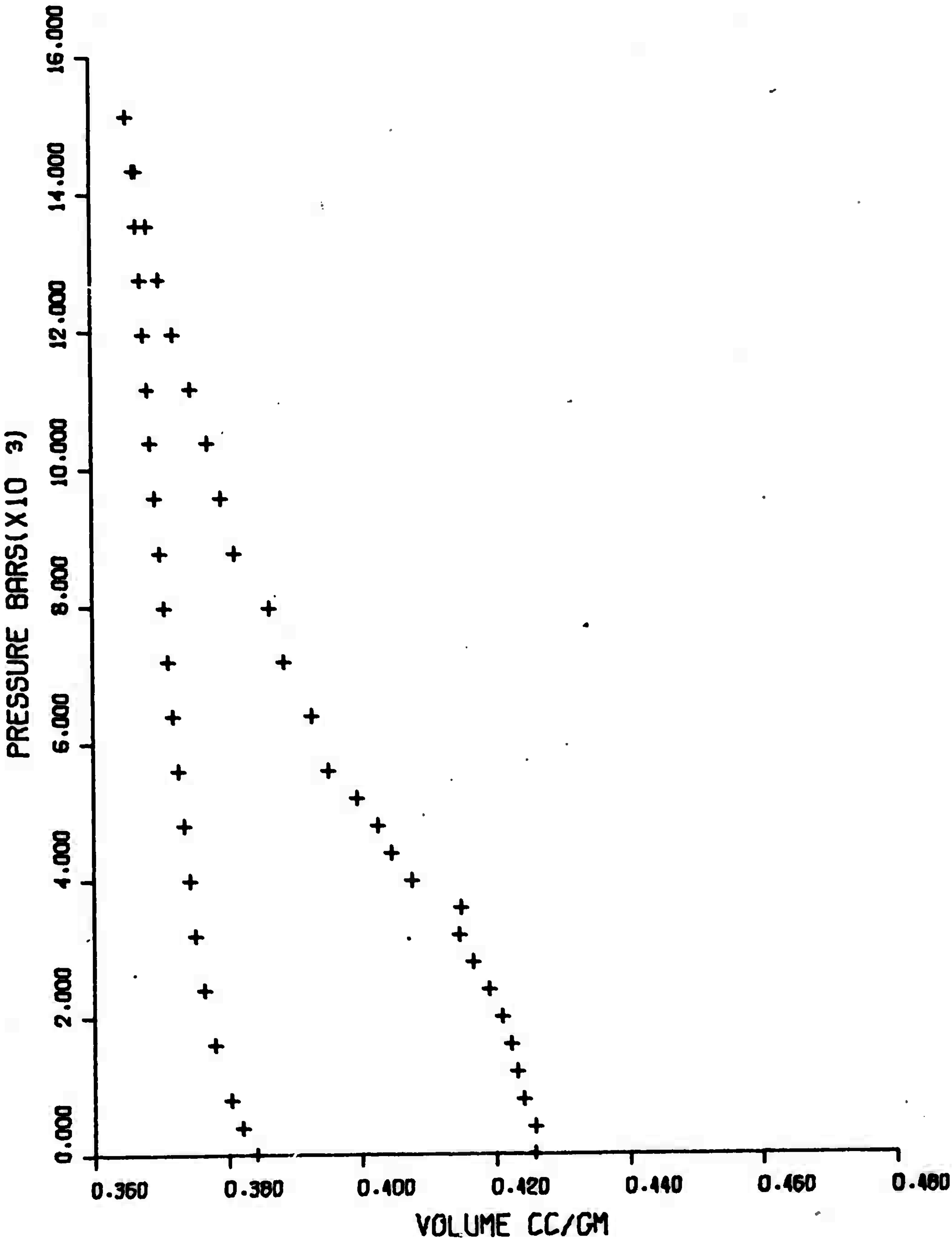
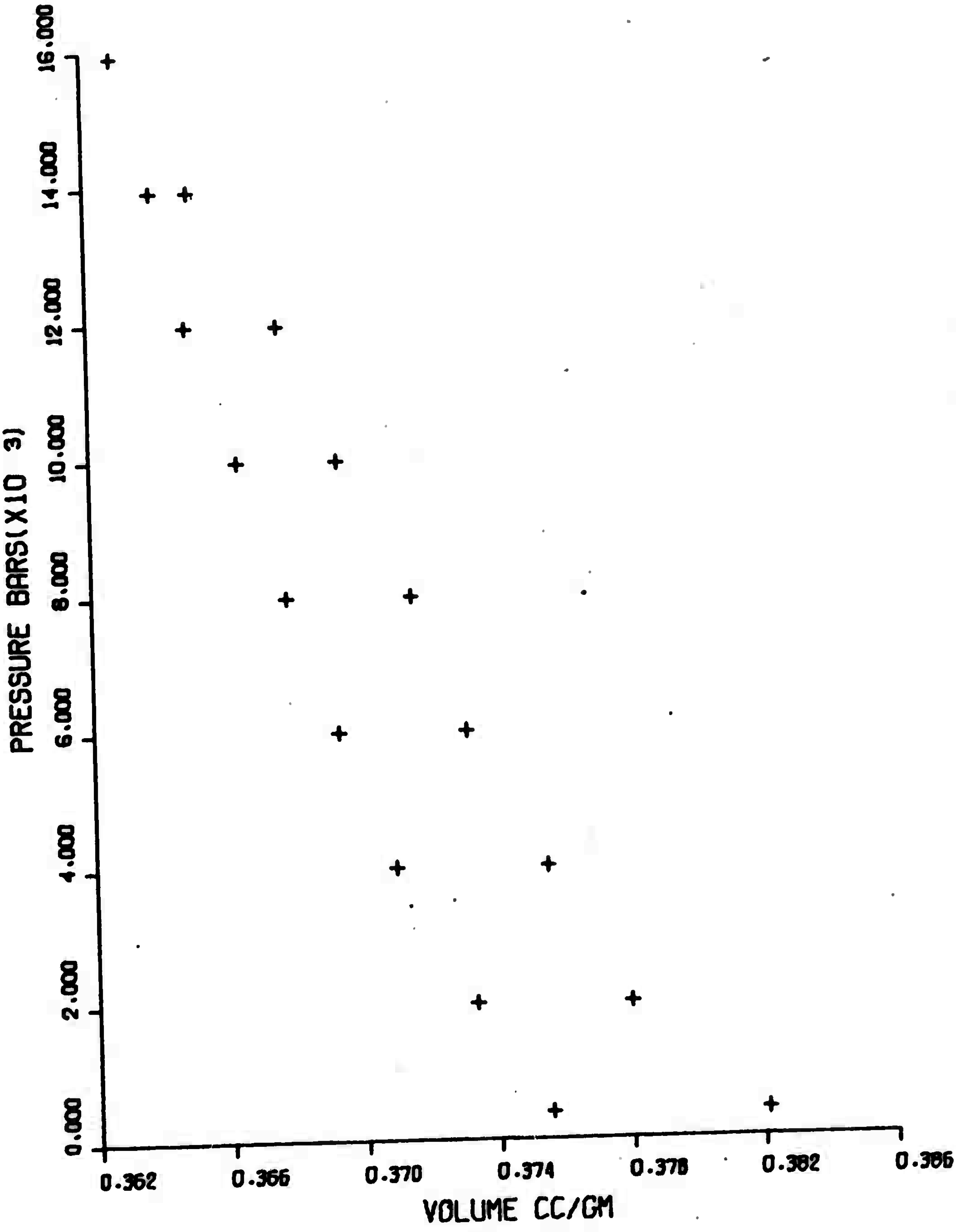
PRESSURE IN BARS	VOL CC/GM	
400.	0.38209	0.37557
2000.	0.37799	0.37333
3997.	0.37556	0.37097
5991.	0.37320	0.36933
7982.	0.37159	0.36784
9970.	0.36938	0.36643
11956.	0.36769	0.36496
13938.	0.36510	0.36399
15918.	0.36290	


16.000
14.000
12.000
10.000
8.000
6.000
4.000
2.000
0.000
PRESSURE BARS(X10 3)
0.360
0.380
0.400
0.420
0.440
0.460
0.480
VOLUME CC/GM

EXP1025-18


PRESSURE BARS(X10 3)
16.000
14.000
12.000
10.000
8.000
6.000
4.000
2.000
0.000
0.362
0.366
0.370
0.374
0.378
0.382
0.386
VOLUME CC/GM

EXP1025-18